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HYDROLOGIC EVALUATION AND RECLAMATION TECHNOLOGIES FOR WESTERN SURFACE COAL MINING

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EXECUTIVE SUMMARY

Introduction

This report presents an analysis of the hydrologic evaluation and reclamation technologies of western surface coal mining as they have evolved and advanced since passage of the Federal Surface Mine Control and Reclamation Act of 1977 (SMCRA). The primary emphasis of this report is threefold, addressing:

1. Hydrologic data used in the preparation and review of mining and reclamation plans. Data are assessed with respect to types, sources, availability, and adequacy from the standpoint of spatial and temporal distribution.
2. Analytical techniques used to predict and evaluate the hydrologic impacts of mining and to design facilities and procedures to identify and/or restore premining hydrologic functions.
3. Evaluation criteria used to determine the success of hydrologic restoration.

This report also discusses special reclamation practices used to preserve and restore the essential hydrologic functions of alluvial valley floors. Uncertainties that exist in hydrologic restoration are identified, and research topics that may help to resolve these uncertainties are suggested. Innovative procedures or practices that have been developed for hydrologic restoration in western surface coal mines are also discussed.

This report examines surface coal mining in the states of North Dakota, Montana, Wyoming, Colorado, and New Mexico. Climates of the coal mining areas are arid to semi-arid, and the majority of streams directly affected by mining are ephemeral. Perennial streams and tributaries are generally situated in alluvial valley floors significant to irrigated agriculture, and no mining will be allowed that would preclude farming in these areas with the exception of areas permitted before 1977. Some impacts to perennial streams may occur, however, due to removal of the coal seams and disturbance of overburden aquifers which may affect the quality and quantity of groundwater discharge to these streams.

Aquifers affected by surface coal mining are, in most cases, shallow because the maximum overburden depth that can be economically removed is generally about 150 feet. Shallow aquifers encountered include the coal itself, overburden sandstones, and, in some areas, alluvial deposits and porcelanite. Water quality in aquifers directly affected by western surface coal mining is generally suitable for livestock use but marginal to poor for irrigation and domestic uses.

Data

There are two major sources of hydrologic data used by western surface coal mines. The first is the U.S. Geological Survey (USGS). The USGS publishes surface-water records including water quantity and quality data annually in a water-data report for each state. Groundwater levels and quality data are also published annually. In addition, the USGS has three primary water-data management and acquisition programs which provide access to existing hydrologic data.

The second major source of hydrologic data are mine permit application documents. Large quantities of surface-water and groundwater data are collected by mining companies throughout the west in order to provide premining baseline data. Monitoring continues both during and after mining to provide data for use in determining effects of mining and success of reclamation practices. Data collected are submitted to the regulatory agencies on a regular basis, generally either quarterly or annually, and incorporated in the annual reports and permit application documents of the mining companies.

Data availability is often not adequate for the intended purpose of establishing baseline conditions. USGS streamflow data are generally collected on perennial and intermittent streams, while the majority of streams directly affected by surface mining in the west are ephemeral. For this reason, USGS data are generally not available for establishing baseline conditions within the mine permit area. Streamflow quantity and quality data collected by the USGS are primarily used for regional cumulative hydrologic impact studies (CHIAs). Groundwater data are also not generally available from the USGS for a specific mine permit area but are generally available for a regional assessment of groundwater resources and uses in adjacent areas.

Data collected by the mining companies are also often not adequate for the intended purposes. Monitoring programs conducted by some mines have quality control and assurance problems. Cases of incorrectly installed equipment and improperly reduced data were documented during the course of this investigation. Data adequacy, particularly for groundwater quality, has improved since enactment of SMCRA because of more stringent monitoring requirements. In states which have developed guidelines for the collection of hydrologic data, the quality of the data is generally better and more complete than in states without such guidelines.

Reporting of data to the regulatory authority varies from state to state and even from mine to mine within a state. Because there is no standardized format for the reporting and compilation of data, locating specific data among the permit application documents and related reports is, in most cases, difficult. Of the states studied herein, only one has published a guideline designed to standardize the format of mine-permit application documents. Standardized formats for these documents, which frequently consist of up to 20 or more volumes, greatly facilitate the locating and review of hydrologic data and analyses.

A common problem with the data from surface mine monitoring programs is the lack of goals for the monitoring programs. Extensive hydrologic data for the mine permit area and the surrounding region are often collected with no specific goal in mind. As a result, data collection often becomes a perfunctory practice and the data collected are frequently not useful for any specific purpose.

The sheer volume of the hydrologic data collected by the mining companies creates data-management problems. Surface-water and groundwater monitoring programs consist of extensive networks of surface-water gaging stations and groundwater monitor wells. Water quantity and quality data from the stations and wells is generally collected quarterly or more often, and each water-quality sample may be analyzed for up to 30 or more chemical and physical parameters. This results in a large quantity of data to be compiled by the mine operators and submitted to the regulatory authorities each year. Data management is also a problem for regulatory authorities because of the number of mines which submit these large volumes of data each year.

Steps are being taken that will eventually improve data collection and management. These steps include development of more specific guidelines and monitoring requirements by regulatory agencies and development of computerized data-management systems. Periodic and critical evaluation of monitoring programs and the data obtained should be widely implemented to improve the quality of data and eliminate the collection of redundant, superfluous or incorrect data.

Analytical Techniques

A variety of analytical techniques are commonly used to design methods to protect and restore surface-water drainage systems disturbed by surface coal mining. Some form of the SCS triangular hydrograph technique is most commonly used to predict peak flows and runoff volumes. The trend toward the use of the SCS rainfall-runoff method has resulted because this method is based on site-specific watershed characteristics and can be used to compare premining, during mining, and postmining conditions, and because a runoff hydrograph is calculated which can be used in flood-routing studies. A contributing factor to the growing use of the SCS method is the availability of computer models to perform the calculations.

Erosion and sediment delivery from surface-mined lands are generally estimated using the Universal Soil Loss Equation (USLE), an equation for estimating gross erosion rates. The gross erosion rate is combined with an appropriate sediment-delivery ratio to estimate sediment yield from both disturbed and undisturbed lands.

State and Federal surface-mining regulations require that sediment from disturbed lands be controlled. The regulatory authorities have generally taken the position that sedimentation ponds are the best available control technology. Sedimentation ponds are point sources of pollution, and discharges from these ponds must meet Federal point-source effluent standards for suspended-solids (or settleable solids) concentrations. Because the western United States is a generally water-short area, and because increasingly large areas are becoming subject to sediment-control requirements as mining proceeds, there is a growing awareness that alternative sediment-control techniques may be preferable to sedimentation ponds in some cases. Technologies for the design and implementation of alternative sediment-control practices are well developed. However, potential conflicts may result from the lack of specific criteria with which to evaluate alternative forms of sediment control. If effluent quality is the only criterion, sedimentation ponds will remain the primary means of sediment control. However, if other factors are considered, such as ambient water quality, water conservation and cost-effectiveness of control techniques, alternative sediment controls may be more widely employed in the future.

Regional models are often used to predict impacts to surface-water quality. The models use a water-budget and mass-balance approach to estimate changes in surface-water quality caused by surface mining. The models may be either computer or hand-calculation models.

Design of stable restored surface-drainage systems is a critical aspect of surface-mine reclamation. A technology is developing whereby the design of restored drainage systems is based on an integrated approach employing both quantitative geomorphic and hydraulic analyses of the premining drainage systems. It is obvious from this investigation that in some states much more attention to design of restored surface-drainage systems is needed.

The groundwater-flow systems affected by mining are analyzed using one of three methods. These are: (1) extrapolation of historic data, (2) manual calculations wherein the mine is assumed to simulate some combination of wells and line sinks, enabling the use of standard groundwater equations, and (3) simulation of the groundwater effects of mining through the use of digital computer models. Groundwater analytical techniques are not specified by regulatory authorities. Each of the preceding methods can provide valid results under certain conditions; however, this investigation showed that few mine-permit applications contain justification for the method selected. No regulatory authority has implemented a program wherein monitoring programs are specifically designed to confirm or refute predictions of groundwater impacts, and therefore it cannot be stated whether any analytical technique is more precise than any other for any given mine plan or set of hydrogeologic conditions.

Postmining groundwater quality is predicted using one of two methods: (1) by determining the water-soluble constituents of the spoil through batch mixing, saturated paste analysis, or column-leach studies, or (2) using digital computer models which simulate hydrogeochemical processes that affect spoil-aquifer water quality. The first method is most commonly used in the western United States.

Analytical techniques used in the hydrologic restoration of alluvial valley floors (AVFs) consist of studies of premining channel and flood-plain geometry, erosional stability, and alluvial aquifer depth, thickness, and water storing and transmitting capabilities. The postmining AVF is designed to restore those premining characteristics that are determined to be essential hydrologic functions (EHF) of the premining AVF. In addition, mining procedures must be designed and conducted so as to prevent material damage to the EHF of off-site AVFs.

The analytical techniques used by western surface coal mines are becoming more sophisticated as time goes by. It is not known, however, whether the accuracy of the techniques is improving because no state has a program specifically designed to verify and modify, as required, any predictive techniques. There is a need to place more emphasis on the design of hydrologic monitoring programs to yield data specifically required for calibration and verification of protective techniques.

Evaluation Criteria

The criteria for evaluation of restoration of hydrologic systems are quite general. Regulations require that disturbance to the prevailing hydrologic balance be minimized, but there are few specific criteria to determine whether this is being done. Restored land must be graded and vegetated to provide erosional stability, and the minimum design storm for permanent diversions of perennial and intermittent streams is specified by regulation. Bond release cannot occur unless lands are not contributing suspended solids to streamflow above natural levels or above established receiving-water standards. Lack of baseline TSS data and wide variations in natural TSS levels make this bond-release criterion difficult to enforce.

Monitoring programs are designed to provide data on streamflow quantity and quality, but few criteria exist for actually utilizing the data to evaluate reclamation. Reclamation designs for restored channels are evaluated during the mine permit review and approval process, and reclamation progress is reviewed during compliance monitoring. The success of restoration cannot always be determined, however, because the bond-evaluation period is not long enough to make it likely that a runoff event of sufficient magnitude to test the design will occur within a reasonable time after reclamation is deemed complete.

Evaluation of aquifer restoration is based on prevention of pollution of subsurface water. However, there are no established numerical quality standards to define pollution in this context. There are also no standards for quantitative evaluation of spoil-aquifer hydraulics or recharge rates.

Postmining groundwater monitoring programs are established, usually by negotiations between the mine operator and the regulatory authority, to determine if "pollution" is occurring. The time required for disturbed aquifers and spoil aquifers to attain hydrostatic and chemical equilibrium may be much longer than the bond-evaluation period. Therefore it may be difficult to evaluate the success of aquifer restoration. Currently, the most common technique for evaluation is a simple, subjective comparison of premining aquifer characteristics with predicted postmining characteristics. Postmining groundwater quality is generally considered adequate if the water is suitable for the same uses as the premining groundwater.

The evaluation criteria for determining success of restoration of alluvial valley floors are more specific. Reestablishment of essential hydrologic functions and premining agricultural productivity are required for bond-release. Monitoring programs usually duplicate the premining monitoring to determine if the essential hydrologic functions have been restored. Considerable time may be required, though, for the restored alluvial valley floor to reach equilibrium, indicating that uncertainties as to the ability to restore all AVF hydrologic functions may persist for some time.

As mentioned previously, there is a need to develop and implement meaningful criteria with which to evaluate alternative sediment-control technologies.

Additional Research Needs

This investigation has revealed that additional research is needed on the following topics:

1. The relation of overburden lithology, mining techniques and long-term settling of spoils to spoil-aquifer hydraulics.
2. Improved methods of predicting spoil-water quality.
3. Verification and refinement of rainfall-runoff models and groundwater-flow models.
4. Effectiveness of alternative sediment control.
5. Quantitative definition of toxic and acid-forming overburden, and, when it is placed in proximity to stream channels, definition of proximity.
6. Cumulative effects on the quality of groundwater passing through the spoils of more than one mine.
7. Criteria for disposal of power-plant wastes in mine backfill.
8. Methods for determination of recharge by surface infiltration.
9. Criteria to quantitatively evaluate hydrologic restoration.
10. Improvement of spoil-aquifer hydraulics and water-quality characteristics through innovative material-handling techniques.

GLOSSARY OF SELECTED TERMS USED IN THIS REPORT

AQUIFER--A body of earth strata capable of transmitting water through its pores at a rate sufficient for water supply purposes.

AQUITARD--Natural material that stores water and also transmits enough water to be significant in the study of the regional migration of groundwater, but not enough water to supply individual wells.

BASE FLOW--That portion of the stream discharge which is derived from groundwater outflow or other sources outside the net rainfall which created the surface runoff.

CREST-GAGE STATION (or CREST-STAGE GAGE STATION)--A simple measuring device used to obtain a record of flood crests at sites where recording gages are not present.

CUMULATIVE HYDROLOGIC IMPACT ASSESSMENT (CHIA)--A determination of the probable additive impacts to surface and groundwaters associated with all existing and anticipated mining in an area.

DISCHARGE--In its simplest concept, discharge means outflow of water; therefore, the use of this term is not restricted as to course or location and it can be applied to describe the flow of water from a pipe, aquifer or from a drainage basin. Flow rates in canals or streams are often referred to as discharge rates. It is also correct to speak of the discharge of a canal or stream into a lake, stream or ocean.

AVERAGE DISCHARGE--Arithmetic mean of numerous discharge rate values.

PEAK DISCHARGE--Peak flow rate. The term is normally used in regard to the peak flow rate in a stream during a flood event.

DISSOLVED--Carried in the fluid state and not in suspension. The term usually is in regard to the chemical constituents in solution in surface or groundwaters.

DIVERSION--(1) The act of taking water from a stream or other body of water into a canal, pipe, or other conduit. (2) A man-made structure for taking water from a stream or other body of water.

DRAINAGE AREA--The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide. It is expressed in acres, square miles, or other units of area.

DRAINAGE BASIN--A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

ELUTION--The removal of soluble matter by washing with water.

EPHEMERAL STREAM--A stream that flows only in direct response to precipitation, and thus discontinues its flow during dry seasons. Its channel is above the level of the water table.

GAGE HEIGHT--The water-surface elevation referred to some arbitrary gage datum. Gage height is often used interchangeably with the more general term stage, although gage height is more appropriate when used with a reading on a gage.

GAGING STATION--A particular site on a stream, canal, lake, or reservoir where systematic observations of gage height or discharge are obtained.

GEOMORPHOLOGY--That branch of both physiography and geology which deals with the form of the earth, the general configuration of its surface, and the changes that take place in the evolution of land forms.

HEAD--Pressure of a fluid upon a unit area due to the height at which the surface of the fluid stands above the point where the pressure is determined.

HYDRAULIC CONDUCTIVITY--Ratio of flow velocity to driving force for viscous flow under saturated conditions of groundwater in a porous medium.

HYDRAULIC GRADIENT--(1) Pressure gradient. As applied to an aquifer it is the rate of change of pressure head per unit of distance of flow at a given point and in a given direction. (2) As applied to streams, the slope of the energy grade line, or slope of line representing the sum of kinetic and potential energy along the channel length.

HYDROGRAPH--A graph showing, for a given point on a stream or conduit, the stage, velocity of flow, available power, or other function of the discharge with respect to time.

RUNOFF HYDROGRAPH--A time record of stream-surface elevation or stream discharge at a given cross section of the stream.

HYDROSTRATIGRAPHY--The study of the relationships between the occurrence and characteristics of groundwaters and the geologic features of the rock units forming aquifers.

INTERMITTENT STREAM--One which flows only at certain times of the year when it receives water from springs or from some surface sources such as melting snow in mountainous areas.

PERENNIAL STREAM--A stream which flows at all times.

pH--Measure of acidity or alkalinity of water. Distilled water, which is neutral, has a pH value of 7; values above 7 indicate the presence of alkalines, while those below 7 indicate acids.

PIEZOMETER--An instrument for measuring pressure head in a conduit, tank, soil, etc. It usually consists of a small pipe or tube tapped into the side of the container, the inside end being flush with, and normal to, the water face of the container, connected with a manometer pressure gage, mercury or water column, or other device for indicating pressure head. Certain wells can be used as piezometers to measure pressure heads in aquifers.

POINT SOURCE--A single source of contamination to surface or groundwater. However, point source may refer to a highly localized area of surface or groundwater contamination.

POTENTIOMETRIC SURFACE--Surface to which water in an aquifer would rise by hydrostatic pressure.

PROBABLE HYDROLOGIC CONSEQUENCES (PHC)--The projected effects of a mining operation on the quality and quantity of surface and groundwater; depth to groundwater; surface and groundwater flow, timing and pattern; the stream channel conditions; and the aquatic habitat.

RUNOFF--That part of the precipitation that appears in uncontrolled surface streams, drains or sewers. It is the same as streamflow unaffected by artificial diversions, imports, storage, or other works of man in or on the stream channels.

RUNOFF CURVE NUMBER--Used to determine the amount of direct runoff from a storm. The curve numbers are based upon soil groups, land use, cover and land treatment. The higher the curve number, the greater the amount of direct runoff to be expected from a storm.

RUNOFF HYDROGRAPH--A graph showing, for a particular watershed, discharge versus time for a rainfall event.

SATURATED THICKNESS--The portion of a stratum where all of the voids are completely filled with water.

SEDIMENTATION POND--A primary sediment-control structure designed, constructed and maintained to slow down water runoff to allow sediment to settle out; includes barriers, dams or excavated depressions.

SPECIFIC CONDUCTANCE--The ability of a substance to conduct an electrical current. Chemically pure water has a low specific conductance because there is little dissolved material present. Specific conductance can be used to estimate total dissolved solids. Expressed in micromhos per centimeter (umhos/cm).

SPOIL MATERIAL (SPOILS)--The replaced overburden removed during mining to expose the sought-after mineral; does not include the marketable mineral, subsoil and topsoil.

STATION--Ground position at which the geophysical instrument is set up for observation in the field.

PARTIAL-RECORD STATION--Particular site where limited streamflow or water-quality data, or both, are collected systematically during a period of years for use in hydrologic analysis.

STORAGE COEFFICIENT--(1) For surface waters, a coefficient devised by Allen Hazen to express the relation of storage capacity in a reservoir, to the mean annual flow of a stream above the dam forming the reservoir. (2) For groundwaters, the cubic feet of water discharged from each vertical column 1 ft. square as the water level drops 1 ft.

STORATIVITY--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Equivalent to storage coefficient.

STREAMFLOW--The discharge that occurs in a natural channel. Although the term discharge can be applied to the flow of a canal, the word streamflow uniquely describes the discharge in a surface stream course. The term "streamflow" is more general than runoff, as streamflow may be applied to discharge whether or not it is affected by diversion or regulation.

SUSPENDED SEDIMENT--The very fine soil particles which remain in suspension in water for a very considerable period of time without contact with the bottom.

TOTAL DISSOLVED SOLIDS (TDS)--The total quantity of chemical constituents or elements in solution in ground or surface waters.

TOTAL SUSPENDED SOLIDS (TSS)--The velocity-weighted concentration of suspended sediment expressed as milligrams of dry sediment per liter of water-sediment mixture.

TIME OF CONCENTRATION--The time required for water to flow from the farthest point on the watershed to the gaging station or other point of interest.

TRANSMISSIVITY--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Commonly expressed in gallons per day per foot (gpd/ft).

WATERSHED--All lands enclosed by a continuous hydrologic drainage divide and lying upslope from a specified point on a stream.

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HYDROLOGIC EVALUATION AND RECLAMATION TECHNOLOGIES FOR WESTERN SURFACE COAL MINING

1.0 INTRODUCTION

1.1 Purpose

During this investigation the hydrologic evaluation and reclamation technologies of western surface coal mining as they have evolved and advanced since passage of the Federal Surface Mine Control and Reclamation Act of 1977 (SMCRA) were examined. This investigation was conducted under Contract No. 533-1795.0 to the Office of Technology Assessment (OTA) as part of OTA's assessment of Technologies for Western Surface Mine Planning and Reclamation. The primary purpose of this report is to provide OTA with an assessment of:

(a) The data and analytical techniques used by coal companies, Federal and State regulatory authorities, and other interested parties and independent researchers prior to mining to estimate or predict the probable hydrologic impacts of surface coal mining in the Western United States. Hydrologic data used by these various entities is generally described in regard to source, availability, geographical coverage and temporal distribution.

(b) The technologies and methodologies used to mitigate hydrologic impacts during mining and restore the surface-water and groundwater systems after mining.

(c) The data and analytical techniques used after mining to evaluate the success of the restoration of the hydrologic balance.

The preservation and restoration of alluvial valley floors is specifically addressed in Federal and State mining rules and regulations. Accordingly, this report also includes an assessment of the data and analytical techniques used to predict hydrologic impacts to alluvial valley floors. Impact mitigation procedures and special reclamation practices designed to restore the essential hydrologic functions of alluvial valley floors are also identified.

In the report areas where uncertainties that exist with respect to hydrologic restoration at western surface coal mines are identified, reasons for these uncertainties are discussed, and data or research needs necessary to resolve these uncertainties are suggested. At the request of OTA special attention was given to innovative procedures or special mining and reclamation practices that have been instituted in western surface coal mines to enhance the chances of hydrologic restoration.

1.2 Scope

Through SMCRA, the Congress established a requirement that all surface coal mines be covered by a mining permit, specified that certain requirements must be met to obtain these permits, and set forth minimum performance standards that are required of all mine operators. An important feature of SMCRA is that it provides for State regulation of surface coal mining providing that the State programs are not less stringent than the Federal program. However, the Office of Surface

Mining (OSM) still provides oversight to the states that have mines operating on Federal leases. If OSM finds that the regulations promulgated by SMCRA are not being upheld by a state, then a portion or all of that state program can be rescinded by OSM. The five states included in this assessment, North Dakota, Montana, Wyoming, Colorado and New Mexico, all have State programs approved under SMCRA.

Following approval of a State program, all surface coal mine operators within that state at the time the program was approved were required to submit to the State regulatory authority an application for a permit to mine. These permit application documents, submitted in the period since about 1981, were the primary source of information on which this report is based. The information contained in these application documents was supplemented with interviews with State and Federal regulatory personnel, mine operators and other interested parties, literature review, authors' experience, and review of the decision documents prepared by State and Federal regulatory personnel prior to issuance of a mine permit.

1.3 Method of Investigation

1.3.1 Overview

Chapter 2 of this report is an introductory overview of: a) hydrologic data available to surface coal mine operators; b) analytical techniques used to predict site-specific and cumulative hydrologic impacts of surface coal mining; c) the design of impact mitigating measures and hydrologic restoration plans, and d) criteria used by regulatory authorities to evaluate the success or probable success of hydrologic restoration.

The overview section was based on the authors' experience in preparing hydrologic portions of mining and reclamation plans and on the information derived from the various sources described above.

1.3.2 Case Studies

In Chapter 3 of this report case studies of actual mines located within the five states included in this investigation are presented. These case studies were selected based on the authors' experience and on recommendations of regulatory personnel to illustrate a particular use of hydrologic data, data collection or data management technique; prevailing or state-of-the-art analytical techniques or special practices; or a set of evaluation criteria used to determine or predict the success of a reclamation practice.

The case studies were based on reviews of actual mine-permit application documents and regulatory decision documents, as well as interviews with mine operators, regulatory personnel, researchers, and other interested parties.

1.3.3 Analysis

Chapter 4 is an analysis of material presented in Chapters 2 and 3 and of the extent to which various types of hydrologic data are used, who uses them and for what purpose they are used. Needs for new data are identified, and suggestions are made for improvements in utilization of existing data where data are not used, or where they could be used to a greater extent than they currently are. Gaps and uncertainties in the data are noted, and possible means of eliminating these gaps are discussed.

Based on the case studies presented in Chapter 3, the analytical techniques used to predict hydrologic impacts or to design special mining and reclamation practices are evaluated. Uncertainties in the assumptions, computational procedures or data used in the analytical techniques are also analyzed in Chapter 4.

Finally, in Chapter 4 the criteria used to evaluate hydrologic impact mitigation or hydrologic restoration are examined. Where these evaluation criteria are inappropriate considering data or prevailing analytical techniques, or where there are no established evaluation criteria, new or revised evaluation criteria are suggested.

1.3.4 Issues Analysis

In Chapter 5 issues related to hydrology raised by the nature of the data and analytical techniques, by the mining and reclamation methods used to protect and restore the hydrologic balance, and by the criteria used to evaluate the success of that restoration are identified. The levels and kinds of uncertainty which need to be resolved in order to determine the long-term success of hydrologic reclamation are identified, as are the time and resources that will be required to resolve uncertainties; research needs are evaluated, and options for innovation or experimentation in mining and reclamation technologies and methodologies are discussed.

2.0 OVERVIEW

2.1 Introduction

Hydrologic data are required by agencies regulating western surface coal mining for a number of purposes. Baseline data are required to (1) acquaint the reviewing regulatory personnel with the hydrologic characteristics of the permit area and adjacent areas, (2) provide a basis for the establishment of restoration goals and objectives, (3) provide a reference point from which the impacts of mining upon hydrologic functions may be measured and for which the success or failure of hydrologic restoration may be assessed, and (4) hydrologic data are required as input to the various analytical techniques for predicting hydrologic impacts and designing mining and reclamation plans to protect and restore the hydrologic balance.

This chapter begins with an assessment of hydrologic data used in western surface coal mining for the purposes noted above. The data are evaluated with respect to sources, availability, collection and utilization. The chapter continues with an evaluation of the uses of hydrologic data in the various analytical procedures employed to predict hydrologic impacts, design impact mitigation plans and hydrologic restoration procedures, and to evaluate the success of hydrologic restoration or impact mitigation.

The chapter is subdivided into three major sections: surface water, groundwater, and alluvial valley floors. Alluvial valley floors (AVFs) are treated separately in this report because they represent areas where ground- and surface-water interactions are significant and because specific emphasis is placed on AVFs by regulatory personnel.

2.2 Geographical Areas Covered by This Report

2.2.1 Location

The extent of this report is the five western states of North Dakota, Montana, Wyoming, Colorado and New Mexico, further limited to surface coal mines containing Federal non-Indian lands.

2.2.2 Regional Hydrologic Summary

Climates of the coal mining areas within these five states are characterized as arid to semi-arid. Most of the streams in these states, and therefore the majority of streams directly affected by mining are ephemeral, meaning that they flow only in direct response to rainfall or snowmelt events. Perennial streams of the west which support irrigation agricultural activities are protected by AVF legislation and may not be directly affected by mining. However, as discussed in the AVF sections of this report, perennial streams can be indirectly impacted by mining since they receive groundwater discharges that may be altered in quality and quantity by disruption of aquifers during mining and reclamation.

Surface coal mining operations generally affect only shallow aquifers, that is, those from the surface to a depth of about 200 to 250 feet. The maximum overburden depth that can be economically removed is generally about 150 feet, although this depth is a function of the economics of a particular mine. Average coal thicknesses in the areas studied range from about 10 to 15 feet in Colorado, New Mexico and North Dakota to 60 to over 100 feet in the Powder River Basin of Montana and Wyoming. Shallow aquifers affected by mining include the coal itself, sandstones in the overburden, interburden and underburden, and, in some areas, alluvial deposits and porcelanite (baked and fused bedrock created by in-situ combustion of shallow coal seams; also termed scoria or clinker). Based on total dissolved solids (TDS) concentrations, water quality in these shallow aquifers is generally suitable for livestock use, but is only marginal for irrigation use. With the exception of major alluvial aquifers, low yields of wells as well as water quality generally preclude use of these shallow aquifers for irrigated agriculture. Table 1 presents a summary of maximum TDS concentrations in water for various uses. Although water in most of these shallow aquifers generally does not meet recommended drinking water standards for total dissolved solids, many wells for domestic use are completed in the coal seams of Montana and Wyoming.

Table 1. Maximum Recommended Total Dissolved Solids Concentrations in Water for Various Uses

Use	Maximum TDS Concentration (mg/l)
Domestic	500 (recommended) 1,000 (maximum)
Livestock	3,000 (for all classes of livestock) 5,000 (excluding poultry)
Irrigation	500 (for all crops and soils) 1,000 (for all but sensitive crops) 2,000 (may adversely affect some crops and requires careful management) 5,000 (only for salt-tolerant plants on permeable soils with careful management)

Sources: EPA, 1976; National Academy of Science, 1973

Virtually all major perennial streams and their perennial tributaries in the coal fields of the five-state region, including the San Juan River in New Mexico, the Yampa River in Colorado, the Tongue River in Wyoming and Montana, and the Missouri River in western North Dakota, are situated in alluvial valley floors significant to irrigated agricultural activities. With the exception of areas permitted prior to 1977, no mining will be allowed in these AVFs that would discontinue or preclude farming. Direct impacts of any single mine on the streams listed above will therefore be minimal. However, because flows in these major streams are sustained in part by groundwater discharges from overburden and coal-seam aquifers, and because the quality of these discharges may be altered as the aquifers are replaced with spoil material, the potential for cumulative impacts of mining to the hydrologic regime has been the subject of considerable research. Numerous studies on this subject have been conducted for the Yampa, Tongue and San Juan River basins. Issues concerning groundwater and surface-water interactions are addressed in the AVF sections of this report.

2.3 Surface Water Overview

2.3.1 Data

This section discusses surface-water data that are used in the preparation of mining and reclamation plans. Data are discussed with respect to need, sources and availability, temporal distribution, and regulatory requirements for collection and reporting. Uses of the data in various analytical techniques and evaluation procedures are discussed in subsequent sections of the report.

2.3.1.1 Need for Data

Most surface-water data are collected to fulfill one or more of the following specific needs:

a. input data which are used in a particular analytical technique to design a structure or hydrologic feature.

b. reference data from which to measure changes (impacts) during mining and reclamation, and

c. baseline data to describe the surface-water characteristics of the proposed permit area and for use in setting a standard for determining reclamation success.

A baseline surface-water data collection program first involves compilation of existing data in the area, determination of where these data are temporally and spatially deficient, and design of a monitoring program to supply the missing data. Surface-water data necessary to prepare a mining and reclamation plan include:

a. detailed location of all surface-water features, including those upstream and downstream from the permit areas,

b. streamflow quantity data, including seasonal and annual variations, floods and low flows,

c. streamflow quality data, including both physical and chemical characteristics and relationship between discharge and quality,

d. quantification of physical watershed parameters, including topographic features, surficial geology, hydrologic soil groups as defined by the SCS (i.e., Group A--low runoff potential; Group B--moderate runoff potential; Group C--moderately high runoff potential; and Group D--high runoff potential--see U.S.D.I., 1977), vegetative cover, and channel and flood-plain geometries,

e. description of climatic characteristics that affect surface-water hydrology, such as mean annual precipitation, precipitation frequency versus duration relationships, and seasonal and annual variations in precipitation, and

f. a description of surface-water uses within the general area including water rights information and, in some states, information on alternative water supplies that are available for the mitigation of impacts to existing water users.

Reference data for the measurement of hydrologic impacts during mining generally include measurement of streamflow quantity and quality above and below the affected areas and of any discharges originating within the mine boundaries. Measurement of precipitation within the mine property can be helpful in accounting for runoff quantity and explaining changes in streamflow quantity and quality when examined in consideration of regional precipitation frequency and intensity relationships.

Input data for analytical techniques are as varied as the analytical techniques themselves. These analytical techniques and their data requirements are discussed in Sections 2.3.2 and 2.4.2.

2.3.1.2 Sources of Data

One objective of this investigation was to identify sources of surface-water data presented in mine-permit applications and used to predict hydrologic impacts, design water control structures and prepare and evaluate hydrologic restoration plans. While several types of surface-water data are required, there are relatively few sources for the data.

Primary Federal sources of hydrologic data are summarized in Table 2. The main source for streamflow data is the U.S. Geological Survey (USGS), the Federal agency with the primary responsibility for appraising the quantity, quality and distribution of the nation's surface-water and groundwater resources. Through its Water Resources Division the USGS conducts interpretive studies, supports hydrologic research, and maintains data collection networks in all the states. Other Federal agencies play a role in surface-water data collection as their needs arise. The U.S. Bureau of Reclamation monitors reservoir water levels and discharges as a part of the management of their water and power system of dams, reservoirs, and irrigation projects. During the 1970's the U.S. Bureau of Land Management conducted a program called EMRIA (for Energy Mineral Rehabilitation Inventory and Analysis), which was intended to be a coordinated approach to field data collection, analyses, and interpretation of overburden, water, vegetation and energy resource data in the Western coal fields. Various agencies in the Department of Agriculture including the Agricultural Research Service and Forest Service, maintain a limited number of surface-water monitoring sites.

Table 2. Primary Sources of Existing Hydrologic Data

Agency	Program	Summary Description
U.S. Geological Survey	Annual Water-Data Reports	Records of stage, discharge and quality of streams, stage and contents of lakes and reservoirs, and water levels and quality of groundwater. Published annually by State. Reports available for purchase from NTIS.
U.S. Bureau of Reclamation	Water and Power Management	Reservoir water levels and discharge of streams, rivers and canals. Reports available on request from respective regional office.
U.S. Bureau of Land Management	Energy Mineral Rehabilitation Inventory and Analysis (EMRIA), discontinued	Intended to be a coordinated approach to field data collection, analyses, and interpretation of overburden, water, vegetation and energy resource data in the Western coal field. Data compiled in various EMRIA reports available from U.S. Dept. of the Interior.
U.S. Dept. of Agriculture	Various Programs of the Agricultural Research Service, Forest Service, and Soil Conservation Service	Each agency conducts limited monitoring for specific program needs. Data are available from the respective agency on request.
U.S. Environmental Protection Agency	STORET	Computerized database system for storage and retrieval of data relating to water quality, water-quality standards, point sources of pollution, pollution-caused fish-kills, waste-abatement needs, implementation schedules, and other water-quality related information. Any government agency can become a STORET user. The system is accessed by the EPA or by a government agency or university that uses STORET (EPA, 1979).
National Water Well Association (as part of National Center for Ground Water Research established by EPA through Oklahoma, Oklahoma State and Rice Universities)	National Ground Water Information Center (NGWIC)	Computerized retrieval system that searches hydrogeology and water well technology database that resides on a computer at Battelle Columbus Laboratories. Database available to any individual or group upon request or through time-sharing account. Costs assessed for computer time. Geographical coverage is worldwide.

The USGS has a number of ongoing activities that are intended to manage and provide access to the vast amount of existing hydrologic data. In addition to publication of the annual water-data reports for each state, the USGS has three primary water-data management and acquisition programs. These include the National Water-Data Exchange (NAWDEX), the National Water-Data Storage and Retrieval System (WATSTORE), and the Index to Water-Data Activities in the Coal Provinces of the United States. These activities are briefly summarized in Table 3. Additional information on these activities may be obtained from the sources listed at the bottom of Table 3.

Recently the USGS has been compiling a series of reports which describe existing hydrologic conditions and identify sources of hydrologic data in the nation's coal provinces. Public Law 95-87 (SMCRA) requires that mining permit applicants make a "determination of the probable hydrologic consequences of the mining and reclamation operations" in and adjacent to surface mine areas. To aid the permittee in making this determination the law specifies that "hydrologic information on the general mine area prior to mining" be made available by an "appropriate Federal or State agency." This series of reports is intended to provide the required information necessary for the permittee to describe the hydrology of the "general area" of a proposed mine. The information is also intended to aid the regulatory authorities in appraising the adequacy of the applications with respect to determining and minimizing the "disturbances to the prevailing hydrologic balance" during the mining and reclamation process. As of February 1985 reports in the states covered by this investigation had been published for Area 45 in the lower Yellowstone River Basin of Montana (Slagle, et al.,

Table 3. Summary of Major USGS Water-Data Management and Acquisition Programs

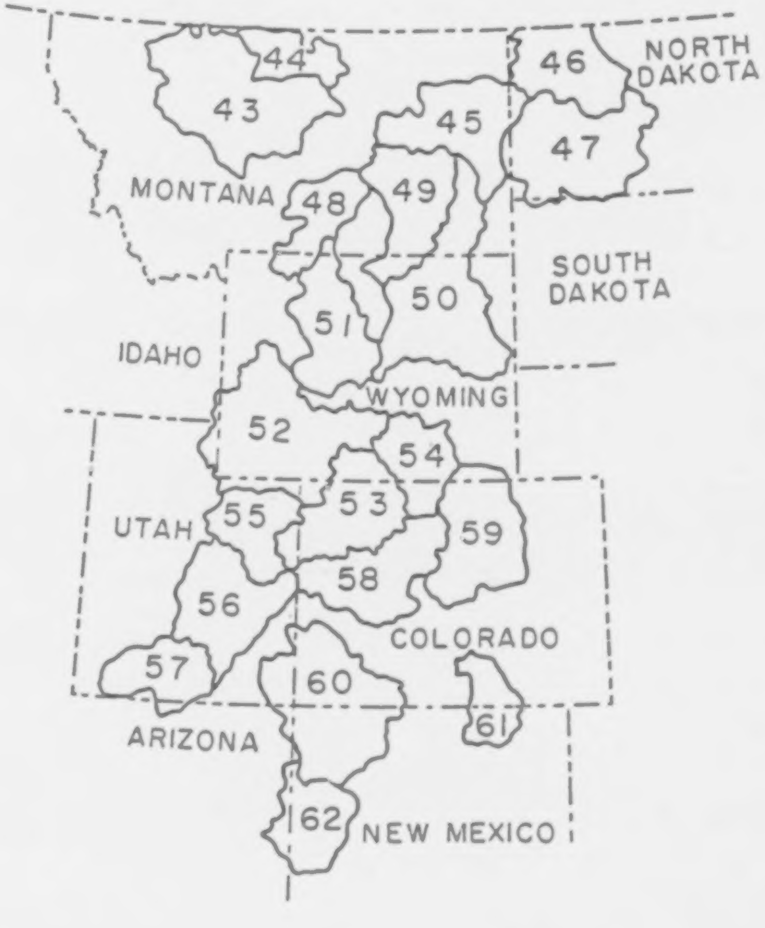
Program	Description	Accessibility	Geographical Coverage
1. National Water-Data Exchange (NAWDEX)	National confederation of water-oriented organizations aimed at making their data more accessible. Services include assistance in identifying and locating needed water data and referring the requester to the organization that retains the data. Master Water-Data Index (MWDI) identifies sites for which water data are available, type of data available, and information necessary to obtain the data. Water Data Sources Directory (WDSD) identifies organizations that are sources of water data and locations within these organizations from which data may be obtained.	Services available to anyone through USGS National Center and Assistance Centers in 45 states and Puerto Rico. Charges for computer and personnel time and duplicating services.	Nation-wide
2. WATSTORE	Computerized system for processing water data and managing data-releasing activities. Includes the following files: Station-Header File (WRD.STAHDR)--an index of sites for which data are stored in DVFILE, PKFIL, QWFILE, and WRD.UNIT (see below). Daily Value File (DVFILE)--daily values for streamflow, reservoir levels, water-quality parameters, and groundwater levels. Peak Flow File (PKFIL)--annual maximum discharge and gage height values at surface-water sites. Water Quality Data File (QWFILE)--results of surface water and groundwater quality analyses. Unit Values File (WRD.UNIT)--water parameters measured more frequently than daily. National Water Use Data System (NWUDS)--a national federal-state cooperative system designed to collect, store and disseminate water-use data.	Information available to anyone through any of USGS Water Resources Division's 46 district offices.	Nation-wide
3. Office of Water Data Coordination (OWDC)	Index to Water-Data Activities in Coal Provinces of the United States. Five-volume index to availability of streamflow, surface water and groundwater quality data and hydrologic investigations in the five major coal provinces. Index was derived from the Catalog of Information on Water Data, a computerized information file about water-data activities in the United States.	Individual volumes available for purchase from USGS. Additional information available from NAWDEX Assistance Centers.	Five major coal provinces of the United States

Sources: U.S. Geological Survey, 1975, 1977, 1984; Kuhn et al., 1983.

1984), Area 49 in the Tongue River Basin of Montana and Wyoming (Slagle, et al., 1983), Area 54 in the North Platte River Basin of Wyoming and Colorado (Kuhn, et al., 1983), Area 60 in the San Juan River Basin of New Mexico (F. Eileen Roybal et al., 1983) and Area 61 in the Huerfano, Purgatoire, Canadian and Vermejo River Basins of Colorado and New Mexico (Abbot, et al., 1983). Figure 1 shows the areas covered by these various reports.

On the state level, data are compiled in the State of Wyoming by the Wyoming Water Research Center (WWRC) which maintains a computerized database and bibliographic storage and retrieval system with flexible methods for the retrieval and analysis of Wyoming water resources data. The computerization process began in 1965, when encoding was started for all regularly reported streamflow data. All regularly reported surface and groundwater quality data, climatological, water well level, and snow course data were added later (WWRC, 1983). The system is operated and maintained on the central computer facilities of the University of Wyoming. The WRDS services are available to any organization or individual by contacting the WWRC office in Laramie, Wyoming. Charges for the WRDS system are assessed to cover the costs of computer and personnel time. Geographical coverage of WRDS is state-wide. No other state studied for this report has a similar program.

In addition to data available through public programs, large quantities of surface-water data are collected by the permit applicants. Surface-water monitoring programs vary from state to state and between mines as a function of the wide range of hydrologic features and of the guidelines developed by the respective regulatory authorities.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NORTH DAKOTA
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MONTANA
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SOUTH DAKOTA
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IDAHO
WYOMING
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UTAH
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58
56
COLORADO
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60
61
ARIZONA
62
NEW MEXICO

Figure 1. Location Map of Hydrologic Areas For Which the USGS is Preparing Regional Hydrologic Reports

Typically, monitoring programs are developed through negotiation between personnel of the regulatory authority and the mining company. Such negotiations usually occur early in the permitting process in order that baseline data may be presented in the application document to facilitate decisions regarding the probable hydrologic consequences (PHC) of the proposed operation. The surface-water monitoring program at any mine may evolve over time, and regulations (30CFR 816.41(e)(3) and corresponding state regulations) require that the monitoring proceed through mining and continue through reclamation until bond release. Some states have developed guidelines to assist permit applicants in developing hydrologic monitoring programs. These are summarized in Table 4. Wyoming has the most specific guidelines and regulations, followed in order by Montana, Colorado, North Dakota and New Mexico. The latter two states have not published hydrologic guidelines, relying on regulations and personal contacts between operators and regulatory personnel to develop hydrologic data-collection programs.

Past practice has been to install continuous water-level recorders on perennial and intermittent streams at the points where the streams enter or leave the mine. Where there is an existing USGS or other recording gage sufficiently close to provide required data, it may not be necessary to install a new station. In such a case the applicant is usually required to assume responsibility for the gaging station in the event that the original operator decides to abandon the site. Stations are generally installed in accordance with USGS procedures (USGS, 1968). Streamflow data are submitted to the regulatory authorities on a regular basis, generally either quarterly or annually depending upon the state and the operator. Water-quality sampling is

Table 4. Summary of Hydrologic Baseline Data-Collection Requirements by State

Type of Data		Colorado (Guidelines and Regulations	Montana (Guidelines and Regulations)	New Mexico (Regulations)	North Dakota (Regulations)	Wyoming (Guidelines and Regulations)
SURFACE-WATER QUANTITY DATA	Perennial	Continuous recording gages. Report Max, Min, and Mean flow.	Continuous recording gages.	Min, Max, and Avg Discharge Conditions identifying low flow and peak discharge rates.	Max, Min, and Avg Discharge Conditions which identify low flow and peak rates.	Continuous recording gages.
	Intermittent	Sample frequency will be dealt with on an individual basis. Determine duration of flow season and peak flow.	Continuous recording gages.	Min, Max, and Avg Discharge Conditions identifying low flow and peak discharge rates.	Max, Min, and Avg Discharge Conditions which identify low flow and peak rates.	Continuous recording gages.
	Ephemeral	Install crest stage recorders. Flow measurement frequency will be dealt with on an individual basis.	Crest stage gages.	Min, Max, and Avg Discharge Conditions identifying low flow and peak discharge rates.	Max, Min, and Avg Discharge Conditions which identify low flow and peak rates.	Monthly reading of crest gages.
	Duration	Not stated.	Not stated.	Not stated.	Not stated. Submit quarterly reports.	Min. of one year of data (see above).
SURFACE-WATER QUALITY DATA	Parameters	Field: pH, EC, Temp, DO Lab: TDS, TSS, Oil and Grease, SAR, HCO3, Ca, Cl, Mg, NO3, NO2, PO4, Na, SO4, Al, As, Cd, Cu, Pb, Mn, Hg, Mo, Se, Zn.	EC, pH, Alk, SAR, TDS, Al, As, Ba, HCO3, B, Cd, Ca, CO3, Cl, Cr, F, Fe, Pb, Mg, Ni, NO3, PO4, K, Se, Ag, Na, SO4, V, Zn.	TDS, TSS, Acidity, pH, Total and Dissolved Fe, Total Mn, others as required by the regulatory authority.	TDS, TSS, EC, pH, Total Fe, others as required.	Field: pH, Temp, EC, Chloride, Alk, Discharge, Turbidity, DO Lab: NH3, NO3, NO2, Al As, Ba, Cd, Cr, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, Zn, HCO3, CO3, Ca, Cl, B, F, Mg, K, Na, SO4, TDS.
	Perennial	Field: measure water quality parameters monthly. Complete chemical analysis quarterly.	Quarterly.	Discuss with regulatory authority. Submit quarterly reports.	Discuss with regulatory authority.	Sufficient to characterize quality - discuss with regulatory authority.
	Intermittent	Sample frequency will be dealt with on an individual basis.	Quarterly.	Discuss with regulatory authority. Submit quarterly reports.	Discuss with regulatory authority.	Sufficient to characterize quality - discuss with regulatory authority.

Table 4. Summary of Hydrologic Baseline Data-Collection Requirements by State (Continued)

Type of Data		Colorado (Guidelines and Regulations	Montana (Guidelines and Regulations)	New Mexico (Regulations)	North Dakota (Regulations)	Wyoming (Guidelines and Regulations)
SURFACE-WATER QUALITY DATA (Continued)	Ephemeral	Sample water for complete chemical analysis twice a year, once during snowmelt, and once during a storm event.	When possible.	Discuss with regulatory authority. Submit quarterly reports.	Discuss with regulatory authority.	Sufficient to characterize quality - discuss with regulatory authority.
	Springs and seeps	Measure field water quality parameters monthly. Sample water for complete chemical analysis quarterly.	Not stated.	Discuss with regulatory authority. Submit quarterly reports.	Discuss with regulatory authority.	Sufficient to characterize quality - discuss with regulatory authority.
GROUND-WATER QUANTITY DATA	Well Density	None specified.	None specified.	None specified.	Min. 1 data point per aquifer per 4 sq. mi.	Min. 3 data points per affected aquifer per sq. mi.
	Pump Tests	Not stated.	Within each affected aquifer.	Not stated.	Not stated.	Within each affected aquifer (2-3 may be adequate).
	Methodology Specified? Y/N	No.	No.	No.	No.	No, but some recommendations are made.
	Static Water Level Frequency	See water quality sampling frequency.	Monthly for at least one year, one well in each aquifer continuously monitored.	Discuss with the regulatory authority.	Discuss with regulatory authority.	Quarterly.
	Potentiometric	Not stated.	For each affected aquifer and next aquifer beneath coal if deemed necessary.	Not stated.	For each affected aquifer and next aquifer beneath coal.	For each affected aquifer.
GROUND-WATER QUALITY DATA	Parameters	Field: pH, EC, Temp Lab: TDS, HCO3, Ca, CO3, Cl, Mg, NH3, NO3, NO2, PO4, Na, SO4, As, Cd, Fe, Mn, Hg, Se, Zn.	EC, pH, Alk, SAR, TDS, Al, As, Ba, HCO3, B, Cd, Ca, CO3, Cl, Cr, F, Fe, Pb, Mg, Ni, NO3, PO4, K, Se, Ag, Na, SO4, V, Zn.	Discuss with the regulatory authority.	TDS, HCO3, Na, Fe, Hardness, NO3, SO4, Cl, pH, SAR, Ca, Mg, EC, others as requested.	Field: pH, Temp, EC, Chlorine, Alk, Turbidity Lab: NH3, NO3, NO2, Al, As, Ba, Cd, Cr, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, Az, HCO3, CO3, Ca, Cl, B, F, Mg, K, Na SO4, TDS.

Table 4. Summary of Hydrologic Baseline Data-Collection Requirements by State (Continued)

Type of Data		Colorado (Guidelines and Regulations	Montana (Guidelines and Regulations)	New Mexico (Regulations)	North Dakota (Regulations)	Wyoming (Guidelines and Regulations)
GROUND-WATER QUALITY DATA (Continued)	Frequency	Bedrock Aquifers: Field parameters monthly. Complete chemical analysis semi-annually. Alluvial Aquifers: Field water quality parameters monthly. Complete chemical analysis quarterly.	Min. of quarterly.	Discuss with the regulatory authority.	Discuss with regulatory authority.	Sufficient to characterize quality in potentially affected aquifers.
AVF SURFACE-WATER QUANTITY		Contact the regulatory authority.	Not stated.	Adequate frequencies to indicate long-term trends. Discuss with regulatory authority.	See above.	See above.
AVF SURFACE-WATER QUALITY		Contact the regulatory authority.	Describe seasonal variations over one full year at a minimum.	Adequate frequencies to indicate long-term trends. Discuss with regulatory authority.	See above.	See above.
AVF GROUNDWATER QUANTITY		Contact the regulatory authority.	Monitoring should be performed at frequencies sufficient to indicate long-term trends. Two years minimum.	Adequate frequencies to indicate long-term trends. Discuss with regulatory authority.	See above.	See above.
AVF GROUNDWATER QUALITY		Contact the regulatory authority.	Monitoring should be performed at frequencies sufficient to indicate long-term trends. Two years minimum.	Adequate frequencies to indicate long-term trends. Discuss with regulatory authority.	See above.	See above.

Sources:

Colorado Mined Land Reclamation Division 1982 Guidelines for the collection of baseline water quality and overburden geochemistry data, permit manual, and 1982 Regulations.

Montana Department of State Lands 1983 Water Resources Guidelines and Guidelines for the Identification of Alluvial Valley Floors and April 1980 Rules and Regulations.

New Mexico Mining and Minerals Division, 1984 Regulations.

North Dakota Public Service Commission, Rules Governing the Reclamation of Surface-Mined Land, June 1983.

Wyoming Department of Environmental Quality - Land Quality Division Guidelines and October 1984 Rules and Regulations.

performed at intervals approved by the regulatory authority and samples are analyzed for a suite of parameters specified by state guidelines or mutually agreed to by the applicant and regulatory personnel.

The technology of gaging streams is well established, and most applicants provide reasonably good data from gaging stations sited on perennial and intermittent streams. Ephemeral streams present a much different case for collection of streamflow and water-quality data. Typically, these streams flow only two to five times a year and only in direct response to rainfall or snowmelt events. The sporadic occurrence of runoff events make it more difficult to collect streamflow quantity and quality data on such streams. A typical installation for collecting data from ephemeral channels consists of a pair of crest-stage gages to provide a means of estimating peak flows and single-stage sediment samplers (Federal Inter-Agency Sedimentation Project of the Inter-Agency Committee on Water Resources, 1961) to enable limited water quality analyses, primarily for suspended sediment.

As illustrated in Section 3.13, quality control and quality assurance problems limit the value of the crest-stage gage data reviewed for this investigation. There are few reliable data on streamflow quality and quantity for ephemeral streams in the coal mining areas of the western states. This lack of data on natural flows and water quality on ephemeral streams has been recognized by various regulatory personnel. To remedy this the Wyoming regulatory authority has proposed a research project to characterize runoff and sediment from mined and unmined small watersheds in the semi-arid environment (Lyle Randen, March 12, 1984, letter to Mr. John Hirschy of OSM). More discussion on this subject is presented in Section 4.1.1.

Data on quantitative geomorphology are presented in the baseline sections of some permit application documents. As described in Section 4.2.1, a wide discrepancy exists in the types and amounts of such data required among the states and even among various regions or districts within a state.

Water-use data are important in identifying appropriators who are subject to impact from proposed mining operations and in assisting regulators and permit applicants in determining such items as the significance of a particular stream or reach of a stream to agriculture or other use. Various agencies in all states have systems of classifying streams based on their suitability for particular uses, and effluent standards are often based in part on the classification of a receiving water with respect to its suitability for aquatic life, domestic water supply, or other criteria. Data on surface-water uses in affected areas are readily available from the applicants' own knowledge of the permit area and from the agency in the respective state that is charged with administering water appropriations and water uses. All the states included in this investigation use the system of prior appropriation as the basis for allocating and permitting water use. Water users must obtain a state permit to appropriate water for most uses, although some small domestic and stock uses are not required to be permitted. Each state has a centralized system where information concerning appropriations can be obtained. These are listed by state as follows:

1. North Dakota Office of the State Engineer, Hydrology Division,

2. Montana Department of Natural Resources and Conservation, Water Rights Bureau,
3. Wyoming Office of the State Engineer, Surface Water Section,
4. Colorado Division of Water Resources, Office of the State Engineer, and
5. New Mexico Office of the State Engineer.

Each of these offices can provide on request a tabulation of existing surface-water appropriations by location, by source of supply, or by type of use (irrigation, stock, domestic, industrial, etc.). Available information includes permit number, location of points of diversion and use, amount of appropriation (flow rate or water volume), name of appropriator, source of water supply, and date of appropriation. More detailed information concerning specific water rights generally requires a search of the files of the respective agency. The water use data are public information available to any person who requests the data. Generally a nominal fee is charged for computer time in searching records and tabulating data and for copying of records. Users of WATSTORE can also access the National Water Use Data System (acronym: NWUDS) listed in Table 3.

Magnitude and frequency of precipitation events are important data requirements in all surface mining operations. Design of hydraulic structures is frequently keyed to such data by regulatory language, such as the requirement to design sedimentation ponds for the 10-year 24-hour precipitation event. Precipitation frequency-duration relationships are readily available from the National Weather Service in various publications (NOAA, 1973, and U.S. Weather Bureau, 1961).

2.3.1.3 Temporal Distribution of Surface Water Data

The distribution of surface water data with respect to time is a key factor in many hydrologic investigations. As described in Section 2.3.2 long-term streamflow data are required at several locations when attempting to construct, calibrate and verify a computer model to analyze the impacts of mining. The availability of such data at the required locations is an important factor in constructing a reliable model.

In spite of certain long-term data needs such as those mentioned above, more serious is the lack of data on ephemeral streams, which are more often directly impacted by mining than are perennial streams. The USGS has only a limited number of partial-record stations in each state, many of which are not located in the coal mining areas. Long-term data are more critical for ephemeral streams due to the wider variability in seasonal and annual flows on such streams.

2.3.2 Surface-Water Analytical Techniques

This section presents an overview of analytical techniques currently used to design surface-water facilities such as diversions and sedimentation ponds, to predict surface-water impacts, and to prepare restoration plans for surface-drainage systems. Information used to prepare this section was obtained from the authors' experience, review of permit application documents, and interviews with regulatory personnel and mine employees.

2.3.2.1 Flood and Low-Flow Estimating Techniques

Peak flows and low flows of streams are important characteristics in describing the hydrology of the permit area and adjacent areas and in determining impacts of mining. Where long-term streamflow data are available, both floods and low flows can be determined through well-established statistical procedures. Flood flow frequency is typically determined using the Log-Pearson Type III distribution method (Beard, 1962). Typically, this method is used to determine the peak flow that is equaled or exceeded at frequencies ranging from 2 to 100 years. It is desirable to have at least 20 years of data in order to perform meaningful statistical analyses (Wahl, 1970).

Perennial streams in the West typically derive the majority of their flows from snowmelt runoff during the spring and early summer. During the high-flow period the chemical quality of these streams is best, and chemical quality declines as surface runoff declines and the groundwater component of flow becomes a larger part of the total flow. Bedrock aquifers in coal mining areas such as the Tongue, Yampa, and San Juan River basins contribute to base flows, and the quality of these discharges is subject to degradation as the shallow aquifers are replaced by mine spoils. After mining, as water levels are reestablished in the spoils and groundwater discharge to the streams occurs from these spoils, the water quality in the streams may be reduced. Low-flow values are typically used to quantify the worst-case stream water-quality degradation that may occur in these perennial streams. A common statistic used to characterize low flows, the 7-day 10-year low flow (Q7,10), is the discharge at 10-year recurrence intervals taken from a frequency curve of annual values of the lowest mean discharge for 7 consecutive days.

Where long-term streamflow data are not available with which to determine flood and low-flow frequencies, two other methods are used. The first of these is the use of regional flood studies. The USGS, usually in cooperation with state highway departments, has prepared a number of regional methods to estimate the magnitude and frequency of flood peaks in intermittent and ephemeral streams. Such methods are often used to predict peak flows for sizing culverts and ditches at coal mines. A regional analysis by Craig and Rankl (1978) provides a means of estimating flood-frequency relations for drainage basins in Wyoming with areas of 0.7 to 11 square miles. Use of this method requires only the use of a topographic map to determine drainage area, basin slope, maximum basin relief, and main channel slope. For drainage basins larger than 11 square miles in Wyoming, another USGS technique is available that requires only the determination of the drainage area or the width of the stream channel (Lowham, 1976). Both the Craig and Rankl and Lowham methods have been determined to be acceptable by the Wyoming regulatory authority for use in the design of diversions or sizing of culverts at Wyoming mines (Wyoming Department of Environmental Quality, Land Quality Division, 1980). Similar studies are available for Colorado (McCain and Jarrett, 1976), New Mexico (Scott and Kunkler, 1976), North Dakota (Crosby, 1975) and Montana (Parrett and Omang, 1981). All these methods are similar in that they make use of readily available data that can be obtained from topographic maps. They do not require actual streamflow data to estimate peak flows.

The second method used to estimate flood flows where no streamflow data are available is the use of rainfall-runoff computational procedures. This method requires knowledge of such watershed characteristics as drainage area, channel slope, relief, and soil and vegetation characteristics as well as precipitation frequency-duration relationships. Input data can be readily obtained from topographic maps, soils maps, observation of vegetation and land-use characteristics, and published precipitation frequency-duration data. Rainfall-runoff models have several distinct advantages over the previously discussed methods of estimating peak flows and runoff volumes. First, because input data include information regarding soils, vegetation and land use, these models can readily be used to compare runoff from a given precipitation event for premining, during mining, and postmining conditions. Second, because they utilize precipitation as a direct input, they lend themselves to regulatory requirements such as the determination of a runoff hydrograph resulting from a specific precipitation event, such as the 10-year, 24-hour storm that is generally used to design sedimentation ponds. Third, rainfall-runoff models can be used to compute a complete runoff hydrograph rather than merely a peak discharge and total runoff volume. The runoff hydrograph can then be used in routing studies to compute a theoretical detention time for a water storage facility or a capacity for a culvert.

Most rainfall-runoff models used by the mine operators are based to some extent on the Soil Conservation Service (SCS) method of estimating direct runoff from storm rainfall (SCS, 1972). This method has its theoretical basis in the well-known unit hydrograph theory (Linsley, et al., 1958, p. 194). For small watersheds and long-duration (e.g., 24-hour) storms, this method becomes calculation intensive, and accurate results can be obtained only with the use of the high-speed computer. As with most other endeavors, the use of computers in mining hydrology has expanded rapidly in recent years. Review of numerous permit applications in the course of this study has shown that many operators are now using computers to calculate rainfall runoff for use in design of hydraulic structures. Programs in common use include TR-20 (SCS, 1965) and TRIHYDRO (Western Water Consultants, 1984). The program SEDIMOT II (Wilson, et al., 1980) can be used to predict the runoff response of a watershed to a particular rainfall event, similar to the first two models, and can also be used to predict both the runoff and sediment response of the watershed. All of these methods require selection of a curve number representative of hydrologic soil groups, vegetation characteristics, and land use within the watershed. The USGS is using the model HSPF (for Hydrological Simulation Program--Fortran model, Johanson and Kittle, 1983) to model the surface-water impacts of mining in the Powder River Basin of Wyoming (Jordan, et al., 1984). This model is the product of a long period of development, testing, and application beginning with the Stanford Watershed Model (Crawford and Linsley, 1966). Its use is documented and guided by a comprehensive manual (Johanson et al., 1981). From a practical standpoint, this model has limited value for operators, regulators, and consultants due to the complexity of the model and the massive amounts of data required for satisfactory operation of the model. Use of various rainfall-runoff models is illustrated in the case studies of Sections 3.3, 3.4, 3.8, 3.9, 3.13, 3.14, 3.17 and 3.20.

In addition to the use of computer models, technical reports based on models are available that enable users to obtain approximate runoff for a precipitation event using a family of curves developed for steep or mild slopes for a particular hydrologic region. Such a method (SCS, 1977) is used extensively by operators in Colorado to design sedimentation ponds and size culverts and ditches (Candace Thompson, Hydrologist for Colorado Mined Land Reclamation Board, personal communication, February 6, 1985). A similar method is used by several operators in Wyoming (SCS, 1971).

The prediction of the runoff response of a watershed to a precipitation event, even with the use of a deterministic (rather than statistical) model such as those described above, is an inexact science. Two different users employing the same method are likely to achieve different results for the following reasons. The majority of rainfall-runoff predictive techniques in use by mine operators require the selection of such watershed characteristics as drainage area, concentration time, and the hydrologic soil-cover complex (runoff curve number or CN). Most also require selection of a precipitation amount and a temporal distribution of this rainfall, such as the SCS Type II rainfall distribution (e.g., Barfield, Warner and Haan, 1981, p. 66). It is unlikely that any two investigators would independently select identical input parameters for the calculation of runoff for a specified storm. Among regulatory personnel there appears to be no general consensus as to a preferred technique, nor is there a uniform method used by regulatory personnel to verify the results of a flood calculation. Selection of a particular method depends upon the capabilities or preferences of the individual performing the calculations. If the reviewing authority believes that a selected CN was too low, leading to a low estimate of runoff volume or peak discharge, conflicts often result. If the selection of a larger CN results in a significantly larger design flood, and hence a more expensive control structure, consequences of redesign can be significant. Most designers are intentionally conservative in their inflow design flood calculations where failure of the structure could have grave consequences such as loss of life or extensive property or environmental damage.

2.3.2.2 Prediction of Surface-Water Quantity Impacts

Individual mines have relatively little impact on the quantity of surface-water supplies in the western states, although even minor impacts can be significant in areas where sources of supply are over-appropriated. In most areas the need for water, for such purposes as dust control on haul roads, exceeds the amount of water available from both runoff and from groundwater intercepted by the pit. In such cases alternative sources, mainly groundwater from wells completed below the coal or in adjacent areas not dewatered by mining, are used to meet water requirements.

During seasons of high runoff or in mines where groundwater intercepted by the pit exceeds water requirements for such uses as dust control, the mine operators must discharge excess water to area streams. Discharges may range from temporary to seasonal to continuous. Seasonal and continuous discharges are generally small in relation to the mean annual runoff volume of receiving streams. On occasion, however, temporary mine discharges can be significant. For example, some of the large mines in the Powder River Basin have encountered large volumes of water in scoria when excavating during facilities construction or when mining near the coal outcrop. The Carter Rawhide Mine breached a large, saturated scoria deposit in 1976 when excavating for the coal preparation plant. It was necessary to pump 6,000 gpm for several days before this deposit was dewatered (General Electric Co., 1979, p. 133). Discharge of this water to the Little Powder River, an intermittent stream, significantly augmented the flow in that stream for several days. Similar conditions were encountered at the North Antelope Mine south of Gillette, Wyoming, with temporary discharges accruing to Porcupine Creek, an ephemeral stream. Such discharges are difficult to predict since the scoria bodies are often discontinuous and in many areas are unsaturated or only partly saturated. Since such discharges are temporary and since this is a water-short area, no adverse impacts result provided the water quality of such discharges is within the range of the water quality generally exhibited by the stream. In the intermittent and ephemeral streams of the western states flow rates and water quality typically are extremely variable. Analysis of the impacts of these temporary discharges on water quantity generally requires a showing that the discharge rate is within the range of natural flows typical for the receiving stream, using either gage data or one of the flood estimating techniques described previously. Such a showing is required to demonstrate, from a water quantity standpoint, that the proposed discharge will not exceed the hydraulic capacity of the stream and therefore create erosional damage downstream from the discharge point. Although such discharges may seem large when entering a stream that has little or no natural flow at the time, these discharges do not approach even the median annual peak discharge of most streams.

Where perennial streams are involved, mining has the potential to decrease streamflows. This occurs where the premining groundwater gradient is toward the stream and this gradient is reversed (i.e., the flow direction during mining is from the stream toward the pit) during mining. Methods for determining such impacts are described in Section 2.4.2.

The requirement for sediment control can also have an impact on streamflows, particularly when considering cumulative impacts of several mines within a single drainage basin. An example of this is described in the cumulative hydrologic impact assessment (CHIA) of mines north of Gillette, Wyoming (Wyoming Department of Environmental Quality, Land Quality Division, 1984). Here, the regulatory authority determined that, "the greatest cumulative impact to the surface-water system will be the reduction in streamflows resulting from the impoundment of runoff in sedimentation ponds and mine pits." Sediment ponds are designed to capture the runoff that would result from precipitation events up to and including the 10-year 24-hour event. These ponds will discharge only when runoff exceeds the 10-year 24-hour runoff volume or after the water has settled for a sufficient time to meet applicable effluent standards for total suspended solids (TSS). The greatest impact to the Little Powder River, as determined by the Wyoming regulatory authority from mine plan maps submitted by the permit applicants, will occur at its confluence with Rawhide Creek. Above this point the flow of Little Powder River could be reduced by as much as 17 percent. This streamflow reduction could cause conflicts between mines and downstream irrigators who depend upon flood flows to irrigate hay meadows. Potential conflicts such as this have led the Wyoming regulatory authority to encourage the use of "alternative sediment control measures" such as straw dikes and porous check dams, which trap sediment but allow water to pass downstream, rather than conventional sedimentation ponds (William Kearney, Chief Hydrologist, WDEQ, January 11, 1985, personal communication). This recommendation is made only where the receiving streams are ephemeral or intermittent, and therefore naturally high in TSS during runoff events, and not for perennial streams which are generally low in TSS and support sport fisheries or other uses which could be adversely affected by discharges high in TSS. Section 3.9 presents a case study which illustrates the application of alternate sediment control technologies.

2.3.2.3 Prediction of Surface-Water Quality Impacts

Effluent limitations for point-source discharges, such as mine sediment ponds, are based on control technology. These limitations are the same whether the discharges accrue to perennial or ephemeral streams, even though the potential impacts from mining are very different for the two types of streams. Runoff to ephemeral streams in the semi-arid West occurs in fine-grained sedimentary materials and high concentrations of TSS occur during most runoff events. Naturally occurring TSS concentrations as high as one million mg/l have been documented (NERCO, 1982). Perennial streams, on the other hand, originate in mountainous areas and derive their runoff chiefly from snowmelt. These streams, such as the Tongue River, the Yampa River, the San Juan River and the Missouri River and their major tributaries, have naturally high-quality water and typically support sport fisheries, municipal and domestic water uses, and large amounts of irrigation.

The potential for water-quality impacts from mining on ephemeral streams is slight. However, water-quality impacts can be significant in perennial streams. These impacts can include:

1. Increase in TSS due to accelerated erosion caused by removal of the vegetative cover, topsoil stripping, and construction of stockpiles, roads, and other facilities. Such impacts are controlled by the use of sediment control structures.
2. Increase in total dissolved solids (TDS) due to discharge of pit water. Point-source discharges are regulated through the NPDES system (P.L. 92-500, Section 402), which assures that certain specified minimum levels of technological control of discharges of pollutants are achieved, and that any water-quality standards established for the receiving waters are met. However, TDS concentrations are not normally included as limited parameters in discharge permits due to the costly treatment technology currently available.
3. Increases in TDS levels in streams after mining and reclamation are complete as a result of the movement of groundwater through replaced spoils to discharge points in perennial stream channels.

Degradation of groundwater quality due to mining is discussed in Section 2.4.2.4 of this report. Reduction in groundwater quality and its impact on water quality in perennial streams has been the subject of considerable study in the Tongue River Basin of Montana (Davis, 1984; Montana DSL, 1982; Thompson and Van Voast, 1981; Van Voast, 1974; Van Voast and Hedges, 1975; Van Voast, Hedges and McDermott, 1977, 1978; Van Voast and Thompson, 1982; Woessner et al., 1979; Woessner et al., 1981; Woods, 1981), the Yampa River Basin of Colorado (Kaman Tempo, 1982; McWhorter, 1975; Parker and Norris, 1983) the San Juan River Basin of New Mexico (Kaman Tempo, 1984). In these areas both the overburden and the coal form integral parts of the bedrock aquifer system that helps maintain the base flows of perennial streams. After mining, the water quality in the spoils is elevated in several constituents, including major ions, TDS, and, in some cases, certain trace elements. After mining and reclamation are complete and groundwater levels are reestablished, the premining flow patterns will resume with water from the spoils contributing to the base flow of the streams. If water in these spoils is significantly higher in dissolved constituents than in the premining overburden and coal, then the stream water quality is subject to degradation. Although the impacts of a single mine may not significantly impact the receiving stream, cumulative impacts of several mines may act together in an additive way to increase surface-water quality impacts. Cumulative hydrologic impact studies are discussed in the next section.

2.3.2.3.1 Cumulative Hydrologic Impact Studies

SMCRA (Section 507(b)(11)) requires that the regulatory authority make an assessment of probable cumulative impacts of all anticipated mining on the hydrology of an area. To date, it has been customary for State regulatory authorities to enlist the aid of the U.S.

Geological Survey, with their vast data sources and hydrologic analysis expertise, to assist in these cumulative hydrologic impact assessments (CHIAs). The OSM has aided by providing funds to the states for this purpose and, in some cases, by hiring contractors to provide independent CHIAs, or by providing the analyses themselves. The following sections describe representative data and analytical techniques that have been used by several investigators to determine cumulative surface-water quality impacts of mining.

The U.S. Geological Survey in cooperation with the U.S. Bureau of Land Management, studied the potential impacts of surface coal mining on dissolved solids in the Tongue River of southeastern Montana (Woods, 1981). This study is described in Appendix A. The USGS Tongue River model simulates some undetermined, future time when all coal mines in the study area are reclaimed and the groundwater flow systems have achieved steady-state conditions whereby groundwater flows through the spoils and into the Tongue River alluvial system. In spite of certain errors, the USGS determined that the model can still meet the objective of assessing the relative magnitude of impacts of surface coal mining in the Tongue River Basin by comparing simulations of present-state conditions to simulations of coal-mining plans (Woods, 1981). Although the model contains errors, many of these errors are traceable to lack of long-term data, and not to an inaccurate theoretical basis. The advantage of a computer model is that, once built, the model can be progressively updated to achieve more accurate simulation of streamflow and dissolved-solids loads.

The simulations conducted with the USGS model (Woods, 1981) indicated that even with intensive mining the dissolved-solids concentrations in the Tongue River do not increase substantially, nor does Tongue River water reach dissolved-solids concentrations unfit for irrigation supply. Certain Tongue River tributaries, including Hanging Woman, Otter, and Pumpkin Creeks, do show significant increases in TDS concentrations with mining; the concentrations are in excess of those considered suitable for irrigation. However, no change in use-suitability results because the three tributaries presently contain water generally considered unsuitable for irrigation (Woods, 1981).

The USGS model described in Appendix A was selected by the Office of Surface Mining (OSM) and the Montana Department of State Lands (DSL) to evaluate impacts of surface mining on the Tongue River for their Tongue River, Montana Petition Evaluation Document (DSL and OSM, 1982). This petition to have certain lands in the Tongue River Basin of Montana declared unsuitable for mining (SMCRA, Section 522) alleged that:

1. Reclamation of lands within the petition area is neither technologically nor economically feasible because of the combination of sodic and/or salty soils and overburden, smectite clays, and shallow soils; and
2. Mining will affect renewable resource lands which will suffer substantial loss or reduction of long-range productivity of water supply and of food and fiber products.

A final decision was made on the Tongue River Petition on December 21, 1981. Both the DSL and the OSM determined that there was insufficient evidence to support the allegation that changes in water quality due to mining would decrease productivity on irrigated lands

(DSL and OSM, 1982). The agencies did not designate any or all of the lands in the petition area unsuitable for surface coal mining. They did state, however, that the decision to deny the unsuitability petition is not a decision to allow mining. All mine-permit applications will still have to go through the permit review and analysis to demonstrate feasibility of reclamation and preservation and/or restoration of essential hydrologic functions.

A somewhat similar analysis was performed for the OSM to determine the cumulative hydrologic impacts of coal mining on the Yampa River Basin in northwestern Colorado (Kaman Tempo, 1982). That investigation is described in Appendix B to illustrate the data sources used for that particular CHIA and to demonstrate how such an assessment can be made without the use of a computer model. Appendix B also contains a description of a second CHIA of the Yampa River Basin performed by the USGS in cooperation with the Colorado Mined Land Reclamation Division (Parker and Norris, 1983). In this latter CHIA a computer model was developed.

The coal mining areas of the Yampa River Basin are similar to those of the Tongue River Basin in that they contain several important perennial streams, and the water quality of these streams is subject to degradation as the overburden and coal aquifers that contribute to base flows are replaced with mine spoils. Eventually, these mine spoils will leach water elevated in dissolved constituents relative to the undisturbed aquifers.

The Yampa River Basin CHIAs described in Appendix B use a water-budget and mass-balance approach similar to that used for the Tongue River (Appendix A) to account for mining-related changes in TDS concentrations at discrete locations on the receiving streams. A primary difference in the OSM CHIA of the Yampa River Basin is that no computer model was developed, and rather than a monthly simulation, as was done for the Tongue River, the impacts were determined for only two cases, historic low flow and mean flow.

2.3.2.3.2 Sediment-Control Measures

The CHIAs described in Appendix A and Appendix B address impacts to perennial streams. Prediction of water-quality impacts of mining on ephemeral streams is much different than for perennial streams because of the lack of interaction between groundwater and surface water. The greatest potential impact to ephemeral streams is an increase in sediment loads (William Kearney, Chief Hydrologist, WDEQ, personal communication, January 11, 1985). An increase in sediment load in ephemeral streams is undesirable for two reasons. The increased sediment, if it reaches a perennial stream, can adversely affect water uses from that stream. Also, if the sediment load in an ephemeral stream is increased to the point that the sediment transport capacity of that stream is exceeded, the stream will become aggradational, creating alterations to the fluvial system that can extend offsite. The requirement for sediment control is clearly stated in Section 515(b)(10)(B) of SMCRA, which is a performance standard that requires a mine operator to prevent, to the extent possible using the best technology currently available, additional contributions of suspended solids to streamflow or to runoff outside the permit area. OSM has taken the position that the best currently available technology for the control of sediment is a properly designed and constructed sedimentation pond. Design of sedimentation ponds is governed by both design and performance standards adopted by each state, which generally require that the pond be designed to meet effluent standards for events up to and including the 10-year 24-hour precipitation event. Federal effluent standards for sediment in discharges from sedimentation ponds (point sources) were recently revised from a suspended-sediment standard to a settleable-solid standard (0.5 ml/l, 40CFR Part 434.40) under certain conditions. It is up to the states as to whether they wish to adopt this newer standard.

At the present time surface coal mines in New Mexico do not use sediment ponds. Rather, the mines construct a berm around the limit of disturbance to theoretically contain runoff from the 10-year 24-hour runoff event. There is no discharge from the mines for runoff events less than the 10-year 24-hour runoff event. The New Mexico Mine and Minerals Division has recently taken the position that sediment ponds are the best available technology and are taking steps to implement design standards for sediment control facilities. A more complete description of this issue is presented in Section 4.2.1.

As previously discussed, in some areas the cumulative impact of sedimentation-pond construction can have adverse impacts by reducing the amount of water available for downstream uses. The Wyoming regulatory authority is therefore encouraging the use of "alternative sediment-control measures" in certain cases. A case study is presented in Chapter 3 (Section 3.9) which illustrates the use of alternative sediment controls under an experimental practice.

Whether designing sediment ponds or planning alternative sediment-control measures, it is necessary to estimate the amount of sediment that will erode from a watershed and be subject to transport downstream during a precipitation event. The most widely used and accepted method of estimating gross erosion is the Universal Soil Loss Equation (USLE), developed by the U.S. Department of Agriculture's Agricultural Research Service, in cooperation with Purdue University. Additional data have led to refinement of USLE parameters and expansion of the use of the equation from solely agricultural lands to non-agricultural lands (Wischmeier and Smith, 1978; EPA, 1977). The use of the USLE is illustrated in a case study in Chapter 3 (Section 3.20).

The USLE is not a precise predictive tool. It is believed that the equation tends to over-estimate soil loss rates. However, the formula is the best available, in the absence of site-specific data (Ettinger and Lichty, 1979). Quantitative estimates of soil loss based on the USLE must be used with caution, but it is felt that the equation is suited for comparisons of alternative projects.

Not all the soil that erodes from the land surface will reach a downstream control point, such as a sediment-control structure. Sediment is deposited at the toes of steep slopes, and sediment deposition results when water velocity is reduced, such as in a straw dike or porous check dam. The total amount of eroded material that reaches a control point is known as the sediment yield. The ratio between the amount of sediment yield and the gross erosion is the sediment delivery ratio. Sediment delivery ratios are commonly estimated from the designer's knowledge of a particular area or from published data, such as that provided by Roehl (1962).

Since mine operators are required to monitor the sediment accumulation in their sedimentation ponds in order to assure maintenance of the required design capacity, empirical data on sediment yields may become available in the future. A substantial amount of analysis will be required to generalize the data to make the derived relationship usable for any watershed other than the one for which it is developed. There are no known plans to conduct such research.

Design of a sediment-control structure requires a calculation of the runoff response of the watershed to a specified precipitation event by one of the flood estimating techniques discussed earlier plus a calculation of the sediment yield, such as with the use of the USLE discussed above. A computer program called SEDIMOT II (Wilson, Barfield and Moore, 1982) has been developed specifically for this purpose. Research of mine plans conducted for the purposes of this report has shown little use of this model. One case study, presented in Chapter 3, (Section 3.9) illustrates the use of the SEDIMOT II model in the planning and comparison of various alternative sediment-control practices.

2.3.2.4 Design of Restored Surface-Drainage Systems

Replacement of an erosionally stable surface-drainage system is critical to the long-term success of surface mine reclamation. Several approaches to restoration of the surface- drainage system have been developed. Selection of the approach depends upon the experience and preference of the operator (or permit applicant), the desires of the regulatory personnel reviewing the application, and the site characteristics. It was found during the course of this investigation that the amount of detail concerning designs of reclaimed surface-water drainage systems ranges from almost none to very elaborate geomorphic and hydraulic studies.

Site characteristics which are subject to alteration by mining include topography (including relief and slope), surficial geology, channel and flood-plain geometry, and drainage basin geometry. The degree to which any of these parameters will be affected is dependent on stripping ratio, areal extent of mining, and mining methods. In many areas the stripping ratio is such that postmining topography can very nearly duplicate premining topography. The overburden swell factor is sufficient to compensate for the amount of coal removed, and the mean elevation of the postmining surface is about equal to that of the premining surface. In such cases it is possible to replace the surface-drainage system to its approximate original configuration. Provided that the premining erosional stability of the drainage system was not dependent upon bedrock outcrops, restoration of stream channels may be simply a matter of restoring premining channel slopes, cross sections and bed form. Bed form here is taken to mean channel bed characteristics, including particle-size gradation for alluvial channels or sod-forming grasses for stabilized channels.

In the Powder River Basin the coal beds are so thick, and the overburden relatively thin, that the drainage system cannot and should not be restored to its original configuration. In such cases entire drainage systems must be built on the restored surface. Complete reconstruction of a drainage system generally requires a complete analysis of the quantitative geomorphology of the premining and postmining drainage basins. To this must be added a detailed hydraulic analysis of each restored channel to help assure that velocities under expected postmining runoff conditions will be nonerosive.

Numerous approaches to the design of restored surface-drainage systems are illustrated by actual case studies in Sections 3.1, 3.3, 3.5, 3.8, 3.11, 3.14, 3.17 and 3.19. The following paragraphs present an overview of the fundamental concepts which form the bases for the approaches to surface-water restoration illustrated in these case studies.

In cases where mining removes only a segment of a stream channel, restoration of that stream-channel segment generally involves duplication of the undisturbed channel cross section, measured on the undisturbed channel above and/or below the disturbed area, together with construction of a longitudinal profile that meets certain criteria. These criteria are upward concavity, no abrupt changes in slope, and a slope that provides non-erosive velocities for the design runoff events. Where necessary, channels and flood plains are made sinuous in order to achieve acceptable slopes.

If the channel is alluvial, i.e., has a sediment bed that causes the sediment transport rate to follow a bed-load function, certain other design criteria may be required, including bed-material size and gradation (size composition). Because the size of the sediment particle that is subject to transport by water is proportional to the velocity of the water, alterations in channel stability can be caused by altering the size gradation of the sediment bed.

In many areas, the channels to be affected are not alluvial but are stabilized with vegetation. In the restoration of stabilized channels the size gradation of the channel bed and bank are not as critical as the ability of the material to support a viable vegetation community. The sediment load carried by stabilized channels is not supplied from the channel bed but from the watershed. This sediment load is termed "wash load" (Chow, 1964, p. 17-37). Wash load consists of very fine particles carried into and through a channel reach with no relation to the bed material. Wash load has no direct effect on the erosional stability of a movable (alluvial) bed or on the bed of a stabilized channel (Wright, 1936). Wash load is of interest in mining since the measurement of wash load, which appears as suspended sediments in the stream, is an indicator of the amount of erosion within the watershed and can be used to help evaluate reclamation.

Caution must be applied when using measurement of suspended sediments as an indicator of reclamation success or of downstream impacts, since wash load, which may be a major portion of the total suspended solids (particularly in stabilized channels), is not a direct function of stream discharge (Chow, 1964, p. 17-37). At the beginning of a storm event much more loose material may be available for transport than at the end of the storm event. Watershed conditions are different for winter than for summer storms, and snowmelt runoff affects different parts of the watershed differently than does rainfall runoff. Thunderstorms can have very small and localized centers, causing some tributaries to contribute more sediment than others. Because sediment supply is not a unique function of discharge, evaluation of channel and watershed reclamation cannot be based on TSS concentrations alone. Sediment is not even a design factor in the restoration of channels stabilized with vegetation. It is important when designing reclaimed channels to distinguish between alluvial channels and channels with stabilized beds.

Design of a restored channel segment disturbed by mining is often based on a detailed hydraulic analysis of the premining channel to determine channel and overbank velocities and hydraulic parameters such as width, depth, roughness coefficient and slope for various flow rates. Design analysis is facilitated by the use of a computerized water-surface profile analysis such as HEC-2 (U.S. Army Corps of Engineers, 1982) or a similar program. Data requirements for this type of hydraulic analysis are only those necessary to compute or select design discharges together with the data from the field survey of the channel cross sections and profiles.

Mines which cover large areas or contain relatively small watersheds must be concerned with more than just the design of restored channels. Entire drainage basins must often be reconstructed, and where the overburden to coal ratio is very large or very small the postmining drainage-basin characteristics may differ substantially from premining characteristics. Some mines in the Powder River Basin of Wyoming have so little overburden and such a thick coal seam that they will have difficulty establishing any surface drainage on the postmining surface. At the Wyodak Mine, for example, a 300-acre topographic depression will be left in the reclaimed surface due to an overburden deficit. The depression is so deep that the floor will be approximately 80 feet below the premining groundwater potentiometric surface in this vicinity. As a result of the low permeability of the coal and spoil materials and the large size of the depression, potential evapotranspiration within the depression will exceed groundwater inflow. Therefore, there will be a perpetual groundwater sink surrounding this depression. Water entering the depression beneath the surface of the spoils will be consumed by evapotranspiration and the dissolved salts will be left behind. Water budget calculations submitted in the permit application indicate that after many years this salt concentration may be sufficiently high that a salt flat will cover a portion of the floor of the depression.

Operators faced with restoration of entire drainage systems base their reclamation plan in part on a quantitative geomorphologic analysis of the premining drainage system and attempt to apply certain relationships from this premining analysis into the design of the restored drainage system. The premining geomorphologic analysis is generally modeled after classical concepts presented by Horton (1945) and Strahler (1950, 1952).

When an area is mined, and the overburden is removed and replaced as spoil, the geologic steady state is upset. The goal of reclamation is to attempt to create a new "steady state" by manipulating the surface, slope and channel configuration so that the newly formed system will once again be in equilibrium with respect to erosional and transportational processes.

Systematic description of the geometry of the drainage basin and its stream-channel system requires measurement of linear aspects of the drainage network, areal aspects of the drainage basins, and relief (gradient) aspects of the channel network and contributing ground slopes. All data for the determination of geometric properties of drainage basins can be obtained from topographic maps. Linear aspects of the drainage network include determination of stream orders, stream lengths, and length of overland flow (Horton, 1945; Strahler, 1952).

Areal aspects of the drainage network include such factors as relation of area to discharge, basin shape, drainage density, and constant of channel maintenance. Relief aspects of drainage basins and channel networks include channel profiles, channel cross-sectional geometry, ground-surface or overland gradients, basin relief, and hypsometric (area-altitude) relationships (Chow, 1964).

Having performed a quantitative study of geomorphic processes and forms of the premining drainage basins, it is necessary to apply the relationships developed to the design of the postmining drainage system. The most important design parameters include channel longitudinal profiles, drainage density and channel and flood-plain cross-sectional geometry.

2.3.3 Evaluation Criteria for Success of Surface-Water Restoration

SMCRA deals only in broad generalities with restoration of drainage systems. Section 508 (Reclamation Plan Requirements) requires general information regarding backfilling and grading and a detailed description of the measures to be taken for the protection of surface-water quality and quantity. Section 515 (Performance Standards) requires the operator to grade restored land so as to effectively control erosion. Regulatory performance standards address the design capacity of "permanent diversions" (30CFR 816.43(b)). However, permanent diversions in the Federal regulations apply only to intermittent and perennial streams. Ephemeral streams, which comprise the majority of streams that will be replaced, are addressed only as "miscellaneous flows" (30CFR 816.43). Bond release criteria (see Table 5) for surface-water restoration are also quite general. All states

Table 5. Summary of Specific Bond Release Evaluation Criteria for Hydrologic Restoration in Colorado, Montana, New Mexico, North Dakota and Wyoming

	Federal (30CFR 700-end)	Colorado 1982 Regs	Montana 1980 Regs	New Mexico 1984 Regs	North Dakota 1983 Regs	Wyoming 1984 Regs
Surface Water						
Evaluate whether pollution of surface water is occurring, the probability of future occurrence of such pollution, and the estimated cost of abating such pollution	30CFR 800.40(b)(1)	3.03.2(2)	26.4.1114(c)	14-40(b)(1)	Bond release keyed to significant environmental harm to water resources 69-05.2-12-11.1	Ch. XVI, Section 3(a)
Evaluate whether lands are contributing suspended solids to streamflow or runoff outside the permit area in excess of requirements set by applicable state or federal law	30CFR 800.40(c)(2)	Required TSS levels keyed to baseline data or data from adjacent nonmined areas 3.03.1(3)(b)	26.4.1116(5)(b)(ii)	14-40(c)(2)	69-05.2-12-12.7.b	Required TSS levels keyed to premining concentrations of receiving waters Ch. XVI, Section 5(a)(B)(II)
Evaluate provisions for maintenance of any permanent impoundments	30CFR 800.40(c)(2)	3.03.1(3)(c)	26.4.1116(5)(b)(iv)	14-40(c)(2)	69-05.2-12-12.7.c	Keyed to State Engineer approval of permanent impoundment Ch. XVI, Section 5(a)(B)(III)
Groundwater						
Evaluate whether pollution of subsurface water is occurring, the probability of future occurrence of such pollution, and the estimated cost of abating such pollution	30CFR 800.40(b)(1)	3.032(2)	26.4.1114(c)	14-40(b)(1)	Bond release keyed to significant environmental harm to water resources 69-05.2-12-11.1	Ch. XVI, Section 3(a)
Alluvial Valley Floors						
EHF reestablished	not addressed (30CFR 807.12 has been rescinded)	3.03.1(3)(b)	26.4.1116(5)(b)(v)	not addressed	69-05.2-12-12.8.c	not addressed

have regulations that require that bonds not be released until the lands are not contributing suspended solids to streamflow above natural levels or above established receiving-water standards.

Operators are required to operate in accordance with their approved mining and reclamation plan, and it is this requirement that provides regulatory authorities with the primary means to evaluate designs of restored surface-drainage systems. All designs submitted are evaluated during the permit application review and approval process, and progress on channel reconstruction is reviewed during compliance monitoring.

2.4 Groundwater Overview

Surface coal mining can affect groundwater resources in two ways. During mining, the pit acts like a large well and creates a cone of depression in the surrounding aquifers. After mining, the shallow aquifers in the mine area are replaced with spoil material which can have both hydraulic and water-quality characteristics that are substantially different from premining values. This section describes the data and analytical techniques used by mine operators to predict and mitigate impacts to the groundwater system, methodologies used to predict or design postmining aquifer characteristics, and criteria used to evaluate the success of groundwater restoration.

2.4.1 Data

This section discusses groundwater data that are used in the preparation of mining and reclamation plans. Data are discussed with respect to need, sources, availability and accessibility, temporal distribution of available data, and regulatory requirements for data collection and reporting. Uses of the data in various analytical techniques and evaluation procedures are discussed in subsequent sections.

2.4.1.1 Need for Data

As with surface-water data, groundwater data used in reclamation planning can generally be classified as input data for a particular analytical technique, reference data for measurement of impacts, and baseline data to establish premining conditions. Ideally, baseline data should be collected from a sufficient number of wells and over a sufficient period of time to allow determination of the spatial variations in aquifer permeability and spatial and temporal variations in static water levels and in water quality. Static water-level data from the mine property and adjacent areas are required to allow determination of flow directions and locations of recharge and discharge areas. Typically, groundwater data-collection programs are developed by negotiations between the permit applicant and the reviewing agency (see Table 4).

A baseline groundwater-data collection program first involves compilation of all existing data in the area and a determination of data deficiencies. A monitoring program is then designed to supply the missing data. Data recommended to prepare a mining and reclamation plan include:

a. detailed location of all groundwater features in the area, including existing wells and springs which may be impacted by the mining operation,

b. geologic data, including surficial geologic maps and geologic cross sections to locate the depth and extent of aquifers, confining layers, and hydrologic barriers and boundaries, including any faults or folds,

c. static water-level data including seasonal and annual variations, for all affected aquifers sufficient for the construction of potentiometric surface maps to determine flow directions and locate recharge and discharge areas,

d. water-quality data for all affected aquifers sufficient to determine seasonal and annual variations and suitability of the water for domestic, irrigation, livestock or other uses,

e. overburden geochemical data for use in predicting postmining chemical quality of the spoils aquifers,

f. results of pump tests to determine permeability, transmissivity, and storage coefficients for all affected aquifers, effects of hydrologic barriers and boundaries, interaction between aquifers, and interactions between the groundwater and surface-water systems.

2.4.1.2 Sources and Availability of Data

The primary source of existing groundwater data are the various reports and databases of the U.S. Geological Survey. These are listed in Tables 2 and 3 and discussed in Section 2.3.1.2, and include NAWDEX, WATSTORE, EPA's STORET, and the Index to Water-Data Activities in Coal Provinces of the United States published by the OWDC. In addition to the previously mentioned databases, the National Ground Water

Information Center (NGWIC) maintains a computerized retrieval system that searches an extensive database of references in the areas of hydrogeology and water well technology (Table 2).

Existing data from operating mines are available in the respective permit application documents and related reports on file with the regulatory authorities. These data are extensive, but considerable effort may be required to locate and extract the data from these files because there is no standardized format for the reporting and compilation of the data.

Data on existing groundwater uses are available from the state agency responsible for administering water appropriations and water uses. These are listed in Section 2.3.1.2, and each agency upon request can provide a tabulation of existing groundwater appropriations by location, depth, type of use, permit number, well yield, name of appropriator, and date of appropriation. In many cases a driller's log and completion report are available. Water-quality data are not generally available from this source.

As illustrated in Chapter 3 (see Sections 3.5, 3.6, 3.7 and 3.8 for example), as a result of the monitoring programs of the mining companies a vast database on groundwater and wells is being amassed for the coal-mining regions of the western United States.

2.4.1.3 Spatial and Temporal Distribution of Groundwater Data

Spatial distribution of groundwater data are generally available to provide a mine-permit applicant with the data necessary to prepare a description of groundwater resources and uses within adjacent areas. Primary data sources are the USGS and data contained in the files of the regulatory authority for other mines in the general area.

Some problems exist regarding the groundwater data collected by mine operators. In general, the quality of the groundwater data available from such sources has improved markedly since the late 1970's. Prior to that time, monitoring requirements were much less stringent, and many operators constructed monitor wells by installing casing in exploration holes. Emphasis was placed on delineating coal and overburden thickness, and the construction of the monitor well was secondary. In many cases insufficient attention was given to well completion, and interformational packers were not used or were used incorrectly. Furthermore, data on overburden lithology and hydrostratigraphy were not obtained, and wells were not properly completed and developed. Very often the casing installed was too small to permit adequate pump testing. Since 1980 well construction and sampling techniques have improved, and the quality of the data obtained has improved accordingly.

A potentiometric surface map represents the static water level of an aquifer at a given point in time, and all data used to construct the map should be obtained concurrently. This is particularly true in areas of active mining where water levels change substantially over time, and in shallow unconfined aquifers where water levels change significantly with changes in season, precipitation, and runoff events. Members of the Gillette Area Groundwater Monitoring Organization (GAGMO), an organization formed by mining companies in the Powder River Basin of Gillette, measure static water levels in their monitor wells on about October 1 of each year and publish the data in annual reports

(GAGMO, 1982 and 1983). These reports are used to show, on an annual basis, the changes in water levels in the shallow aquifers in and around the numerous large coal mines in this region. The GAGMO reports provide an excellent database for the verification of predictive techniques used to determine the cumulative groundwater impacts of mining.

2.4.2 Groundwater Analytical Techniques

This section describes the analytical techniques used to predict pit inflows and resultant drawdowns; to predict and analyze postmining spoil aquifer characteristics and water quality; and to evaluate methods used to restore and protect the groundwater hydrologic balance. Information used to prepare this section was obtained from the authors' experience, review of permit-application documents and published literature, and interviews with regulatory personnel and mine employees.

2.4.2.1 Prediction of Pit Inflows and Associated Drawdowns

Prediction of pit inflows and associated drawdowns requires determination of the hydraulic properties of affected aquifers and knowledge of the mining methods and the mining schedule. Aquifer hydraulic characteristics which must be determined include transmissivity, saturated thickness, storage coefficient, locations of hydrologic barriers or boundaries, and areal extent of aquifers. Long-duration pump tests conducted by the permit applicant enable determination of aquifer hydraulic parameters. Analysis of the pump tests must be done with full consideration of geologic maps and cross sections in order to provide valid results. Selection of the analytical technique depends upon many factors, including site-specific hydrogeologic conditions, pit configuration, and the experience and capability of the investigator.

Review of mine-permit applications and published literature sources during the course of this investigation has shown that the use of digital computer models for evaluating pit inflow, drawdowns and postmining conditions is growing. However, many operators are still using simpler analytical techniques with good results.

For existing mines, where substantial amounts of data are available, pit inflows and drawdowns are determined from historic data. These empirical data are used to estimate inflows and drawdowns that will occur in the future. This situation is illustrated in Chapter 3 for two mines, one in North Dakota (Section 3.2) and one in Montana (Section 3.6). In this case the analytical method used to predict future pit inflows and drawdowns is a simple linear extension of historic trends, and assumes that no changes are made in mining rates or methods and no boundary effects are encountered.

Analytical methods for the computation of pit-water inflows and resultant drawdowns range from simple application of Darcy's Law (Lohman, 1979, p. 10) to comprehensive digital computer models. Brief descriptions of the more prevalent methods are provided in Appendix C, and the use of several of these methods is illustrated in selected case-study analyses presented in Chapter 3. Table 6 presents a summary of the most widely used analytical methods for computing pit water inflows and resulting drawdowns at western surface coal mines.

Any of the first five analytical techniques listed in Table 6 can be used to provide reasonably accurate predictions of pit inflows and drawdowns, provided that the investigator performing the

Table 6. Summary of Analytical Methods Typically Used for Computation of Pit-Water Inflows and Resultant Drawdowns

Method	Data Requirements	Advantages	Disadvantages
Extrapolation of existing data.	Historic records of pit inflows and resulting drawdowns.	Easiest method to use. Proven for given site conditions.	Not applicable for new mine. Not applicable to changing aquifer conditions or mining methods or schedules.
Simple application of Darcy's Law (Lohman, 1979).	Potentiometric surface gradient, aquifer transmissivity.	Simple to use.	Limited predictive tool because either gradient or flow must be assumed. Basic assumptions of aquifer homogeneity and parallelism between base of aquifer and water table seldom met. Hydrologic barriers and boundaries difficult to address.
Theis nonequilibrium radial-flow equations (Lohman, 1979).	Potentiometric heads, aquifer transmissivity and storage coefficient.	Simple to use. Better simulation in most cases than simple Darcy. Can simulate barriers and boundaries with image wells.	Limited predictive tool because drawdown or pit inflow must be assumed. Basic assumptions of aquifer homogeneity, instantaneous release of water with change in head, and infinite aquifer extent seldom met. Radial flow may not occur. Difficult to simulate movement of pit and reduction of aquifer transmissivity in time.
One-dimensional flow equation for fully-penetrating excavation (Departments of the Army, Navy and Air Force, 1971).	Potentiometric heads, aquifer transmissivity, location(s) of aquifer recharge sources.	Simple to use. Good simulation in certain cases.	Assumption that source of recharge and mine pit are infinite in length and parallel not met. Assumption that recharge equals pit inflow not always met. Requires assumption of drawdown or flow.
Combined radial and linear storage-release equations of Jacob and Lohman (1952) and Stallman (1962).	Potentiometric heads, aquifer transmissivity and storage coefficient.	Simple to use. Better simulation of actual pit configuration than previous methods.	Same basic assumptions as Theis equation. Does not consider downgradient flow of water--only storage release.
Finite-difference digital computer model (FDM).	Potentiometric heads, boundary conditions, aquifer transmissivity and storage coefficient, recharge; all must be input for respective nodes.	More accurate than previous methods. Better simulation of moving pit than previous methods. Facilitates accommodation of changes once data input is complete. Capable of handling larger problems, such as cumulative impacts of several mines, than previous methods.	More difficult to use than previous methods. Requires access to computer. Requires substantial calibration and verification. Difficult to check results without independent model study. Need to estimate recharge.
Finite-element digital computer model (FEM).	Same as FDM.	More flexible data input than FDM. More precise results than FDM. Handles irregularly shaped areas and complex boundary conditions better than FDM.	More difficult to use than FDM. Requires substantial calibration and verification. Difficult to check results without independent model study.

calculations does so in full recognition of the assumptions on which the equations are based, the applicability of the selected method to the site-specific hydrogeologic conditions, and the mining methods and schedules. All these methods use data readily available from standard aquifer tests, geologic investigations, and mine-plan maps and figures. The most common mistake made in such studies is to use an equation because of familiarity or convenience that is not appropriate for the conditions that are or will be encountered. In employing these methods to predict pit inflows or drawdowns over the life of a mine, the number of calculations required can become large. Many investigators have employed programmable, hand-held calculators to solve the equations, improving both accuracy and speed of calculation, but not precision. Because of the large number of calculations involved, the investigator will usually select a limited number of pit configurations and perform a few "worst-case" predictions. This often results in the overstatement of predicted drawdowns. Often, worst-case studies are required by regulatory authorities even though unrealistic results will be obtained.

The analytical techniques described above have a common disadvantage; they cannot account for the wide variations in aquifer hydraulic characteristics and boundary conditions normally encountered in real-world situations. These simple analytical techniques do have the advantages that they are widely known and are familiar to regulatory personnel, which facilitates regulatory review.

It has been demonstrated that the use of digital computer models can be a valuable tool in predicting the groundwater impacts of mining. Proper use of the model, including data collection, preparation, calibration and verification, are necessary for a model study to yield valid results. While use of digital computer models is not required by any regulatory authority in the western states, they are becoming more widely used. It can be difficult for regulatory agency personnel to review the adequacy of a computer model study, and it is important when submitting the results of a model study to include a description of the data, calibration and verification techniques, and sensitivity analysis. It is also important to use a model that is widely accepted, well documented, and for which the source code is available.

In recent years the use of digital computer models in groundwater studies has been rapidly gaining popularity. These digital models have many advantages over standard computational techniques, including speed of computation and reproducibility of results, but they are often time-consuming to set up and are more difficult for a regulator to review.

Numerical modeling of groundwater is a relatively new field which was not extensively pursued until the mid-1960's (Bachmat and others, 1980). Since that time, progress has been made in the development and application of numerical models for groundwater management. A mathematical flow model can be used to predict the response of groundwater systems to mining as a function of aquifer parameters (transmissivity and storage coefficient), hydrologic and geologic boundary conditions, and the positioning of the pit within the system being modeled. The flow of groundwater and declines in water level can be described and analyzed mathematically using partial differential equations, provided that adequate hydrologic and geologic information are available. These equations and the concepts on which they are based are well accepted by hydrologists and others dealing with the flow of fluids through porous media. Modern computer methods provide solutions for the equations of flow for complex field problems, and thereby provide means for simulating the operation and response of very complicated systems.

Numerous flow models have been developed by various investigators for various purposes. Bachmat and others (1980) have stated that a model is usable only if it is fully documented (i.e., there is a description of the model, a listing of its code, and a user's manual), available at no cost (such as USGS models or models developed by universities or state agencies), and has been applied once or more in the field. Of a total of 138 flow models surveyed by Bachmat and others (1980), 39 were fully documented, 57 were available to the public, and 106 had been applied in the field, but only 20 met all three criteria and thus were considered usable.

The goal of a groundwater flow model is to predict the value of an unknown variable, such as potentiometric head or discharge rate, at a specific location(s). The application of a groundwater model involves four primary activities (Faust and Mercer, 1980a). These are: 1) data collection, 2) data preparation for the model, 3) history matching or calibration, and 4) predictive simulation. The model should not be used simply as a predictive tool but also as an aid in conceptualizing the aquifer behavior. Two modeling techniques in general use are the finite-difference model (FDM) and the finite-element model (FEM). Data requirements and relative strengths and weaknesses of these models are summarized in Table 6. More detail is provided in Appendix C, together with an illustration of the use of a FDM. The case study in Section 3.12 provides another illustration of the use of a FDM.

At the present time there are two computer models that are frequently used in western surface coal mining, and both are finite-difference models. A model written by the Illinois State Water Survey (Prickett and Lonnquist, 1971) has been used by several mine operators to determine site-specific groundwater drawdown impacts and cumulative drawdown impacts of several mines. An example of the use of this model is provided in a case-study analysis in Chapter 3 (Section 3.12). The U.S. Geological Survey generally uses another finite-difference model (Trescott and others, 1976). A general discussion on the use and data requirements of both of these models is included in Appendix C. Appendix C also includes a description of the USGS's use of the model to examine the geohydrology of the West Decker coal-mining area of southeastern Montana.

Once drawdowns and affected areas are determined, by modeling or another analytical technique, the impact of these drawdowns must be determined by examining existing groundwater uses within these cones of depression. Using water-well data available from the respective state agency (refer to Section 2.3.1) and the drawdowns determined by one of the previous methods, impacts to a particular water user are determined. Wells located close to the disturbed area may be dewatered to the extent that they are no longer usable. In such cases state water laws require the mine operator to replace the water supply or otherwise compensate the owner of the water right for damages incurred. In addition, Federal regulations (30CFR 816.41(b)) and regulations under approved state programs require that the coal mine operator must replace the water supply of the owner of property where his existing water supply has been adversely impacted by mining activities.

2.4.2.2 Determination of Groundwater Quality Impacts During Mining

Impacts to groundwater quality during mining are minimal. Around the pit a cone of depression is created in which groundwater flow is toward the pit. Therefore, there is little opportunity for any contaminants introduced by mining to impact off-site areas. The greatest potential for groundwater quality impacts occurs after mining, when groundwater saturates the spoil and returns to a steady-state (equilibrium) flow pattern. These effects are discussed in Section 2.4.2.4.

2.4.2.3 Predicting Spoil-Aquifer Hydraulics

Surface coal mining removes overburden, extracts the underlying coal, and then replaces the overburden in the mined-out pit. Any aquifers in the overburden and coal are destroyed, and the degree to which their premining functions are restored depends largely upon the physical and hydrogeochemical characteristics of the replaced spoils. The physical characteristics of permeability and porosity, discussed in this section, determine the capability of the spoils materials to store and transmit water. The hydrogeochemical characteristics and their effects on spoil water quality are discussed in the following section.

Premining aquifers in coal and overburden in the western states provide water for both stock and domestic uses. Coal aquifers are generally confined, while overburden aquifers, consisting of sandstone beds contained within a sedimentary sequence of shales and sands, can be either confined or water-table aquifers, depending upon the locale. Most wells completed in these overburden aquifers are capable of producing only small yields of less than 5 to 10 gallons per minute (gpm), sufficient for stock and domestic wells but not for irrigation. The primary exceptions are the alluvial aquifers of major streams, such as the Yampa, San Juan, Tongue, and Missouri Rivers, where much larger well yields are possible. Wells in saturated scoria can also provide large yields. Scoria units can be important sources of recharge to the coal aquifer, with the amount of recharge limited by the permeability of the coal. In general, the scoria aquifers will not be disturbed by mining for two reasons: 1) the scoria was formed by in-situ combustion of coal, and where scoria occurs the coal beds are largely burned away or of low quality due to the effects of weathering and partial combustion; 2) due to the large amount of water stored in the scoria, a barrier of unmined coal is generally left in place to prevent problems which could result when mining approaches too close to a scoria body, allowing water to enter the pit.

Where mining has been occurring for a long period of time, such as the lignite mining areas of North Dakota, the Decker and Colstrip areas of Montana, and the Yampa River Basin of Colorado, substantial amounts of data have been collected concerning the aquifer characteristics of the spoil materials. To date, relatively little research on spoils hydrology has been done in Wyoming and New Mexico. Data are just now beginning to become available on spoil hydraulics in these areas, mostly from research being performed by the mine operators and presented in annual reports and permit applications submitted to the regulatory authorities. Table 7 provides a summary of the predominant sources of spoil-aquifer hydraulic data currently available for these areas.

Table 7. Summary of Major Sources of Spoil-Aquifer Hydraulic Data for Western Surface Coal Mining

State	Mining Area	Primary Investigators	Selected References
Colorado	Yampa River Basin	Mine operators; EPA	McWhorter et al., 1975 McWhorter et al, 1979 Permit documents
New Mexico	San Juan Basin	Few data available	Permit documents
North Dakota	Fort Union Lignite Fields	North Dakota Geological Survey	Groenewold et al., 1979 Groenewold et al., 1983 Moran et al., 1978, 1979 Rehm et al, 1982
Montana	Decker and Colstrip Areas	Montana Bureau of Mines and Geology; Montana Agricultural Experiment Station, MSU	Arnold and Dollhopf, 1977 Hedges et al., 1976, 1980 Van Voast, 1974 Van Voast and Hedges, 1975 Van Voast et al., 1977, 1978 Van Voast and Thompson, 1982
Wyoming	Powder River Basin, Hanna Basin	Mine operators; few data available	Permit documents

Spoil-aquifer hydraulic characteristics are primarily a function of overburden lithology, specifically percent of sand, and mining methods. When the overburden is sandy, spoil materials will likely have sufficient porosity and hydraulic conductivity to serve as aquifers. When overburden aquifers occur chiefly as small, discontinuous sand lenses within a large matrix of clay and shales, the postmining spoils will probably have a low permeability.

Spoil permeability is influenced by mining methods because the swell factor (ratio between volumes of postmining spoils and premining overburden) of recontoured spoils is dependent in part on equipment selection and method of utilization. Overburden removal and replacement is accomplished with some combination of scrapers, trucks and shovels, and draglines. Scrapers are generally used only in small mines, where economics do not permit purchase of large-scale mining equipment such as draglines and electric shovels. Scrapers remove and replace earth in thin lifts requiring numerous hauls. A high degree of compaction results, and the swell factor of the spoils is reduced. The swell factor is important because the increase in volume results in an increase in porosity, which in turn increases hydraulic conductivity (permeability) if the pores are sufficiently large (non-capillary porosity) and interconnected. Trucks and shovels are the dominant mining method in the Powder River Basin of Wyoming. In all other areas studied, draglines are used. Shovels remove the overburden in approximately 40 to 50-foot benches, and trucks dump the spoils into 65 to 70-foot high backfill lifts. Draglines remove overburden at depths of up to about 150 feet and dump the spoil material in the mined-out area forming a series of spoil ridges and valleys which parallel the mining face. In general, the swell factor achieved by truck-shovel mining is between those achieved by scraper and dragline mining. Depending upon lithology, swell factors can be expected to be in the range of 5-10 percent for scraper mining, 10-15 percent for truck-shovel mining, and 20-30 percent for draglines.

Hydraulic conductivity (permeability) of spoils is variable depending on geologic conditions, mining method, and location of test wells as has been demonstrated by studies conducted in Montana, North Dakota, and Wyoming and described below. Spoil-aquifer hydraulic characteristics, transmissivity, permeability and storage coefficient, are determined from standard pump tests, similar to premining aquifer tests. Tests can range from single-well slug tests to long-term multiwell pump tests. Multiwell pump tests are preferable because they enable determination of storage coefficients in addition to transmissivity.

Determination of spoil-aquifer hydraulic characteristics can vary with the location within the spoils of the test well. For example, in a study conducted by the Montana Bureau of Mines and Geology (Van Voast and Hedges, 1975) it was determined that in dragline mines the mine floors become covered with thin strata of coarse rubble composed of wasted coal and boulders that collect at the bottoms of spoil ridges. These rubble zones were theorized to have significantly greater hydraulic conductivity than the overlying fine-grained spoils. In fact, the hydrostatic pressure in these basal strata at the Rosebud Mine near Colstrip, Montana reacts strongly to barometric changes, indicating that the rubble layer is a confined aquifer that has a storage coefficient much like that of the local, undisturbed aquifers. The hydraulic conductivity of the spoils in the Colstrip, Montana area has been found to be similar to that of the confined coal-bed aquifers (Van Voast and others, 1977, p. 1). Therefore, in some areas it appears that, after mining, spoils will not act as barriers to groundwater flow and that groundwater flow patterns will be reestablished in the reclaimed areas and will not differ greatly from premining flow patterns.

The variability of spoil permeability also can be attributed to location of the test well with respect to spoil ridges and valleys left by a dragline as has been demonstrated by studies by the North Dakota Geological Survey (Groenewold and others, 1979, p. 147), based on slug tests performed in dragline spoils at the Indian Head Mine. In general, permeabilities in spoil-valley areas are higher and less variable than those in spoil-ridge areas. There is some indication of a decrease in saturation in spoil ridges as opposed to spoil valleys, indicating preferential movement of water in the base of the spoils through the generally linear spoil-valley areas. This phenomenon has also been reported at the Decker Mine in Montana (Jim Bowlby, Hydrologist for Kiewit Mining and Engineering, March 6, 1985, personal communication).

Few data are available on spoil-aquifer characteristics in the relatively new truck-shovel mines of the Powder River Basin of Wyoming. Initial data indicate that postmining permeabilities will be variable but generally low and in the range of permeabilities measured in the premining overburden. Operators throughout the eastern Powder River Basin have estimated that due to the low permeability of spoil material, it will take from 70 to 2900 years for the replaced spoil aquifer to reach a steady-state condition whereby groundwater flow patterns are reestablished (Wyoming Department of Environmental Quality, Land Quality Division, 1984). These time frames have been determined through groundwater modeling studies of the type previously discussed in Section 2.4.2.1.

Due to the lack of saturated spoils at mines in the eastern Powder River Basin, some mine operators have conducted slug-injection tests on unsaturated spoils in an effort to obtain estimates of hydraulic conductivity using procedures and analytical techniques in common use (Cooper and others, 1967). Results have been inconclusive due to problems with well development in dry spoils, the fact that only a minor portion of the spoil material in the immediate proximity of the well bore is tested in this manner, and the likelihood that the well will encounter rubble zones, voids, buried roads or compacted zones, all common features of each backfill lift. Therefore, a large number of tests would be required to provide an indication of governing spoil hydraulic characteristics. For these reasons the Wyoming regulatory authority no longer encourages aquifer testing of dry spoils (William Kearney, Chief Hydrologist for Wyoming Department of Environmental Quality, Land Quality Division WDEQ/LQD, January 11, 1985, personal communication).

Although there are exceptions, from a study of existing literature it appears in general that mine spoils will not be a barrier to groundwater flow; instead, postmining steady-state flow patterns should closely approximate premining patterns in most areas. The one region where this may not be the case is Wyoming's Powder River Basin, where the coal seams are very thick (70 to 90 feet) and most mines are truck-shovel mines. Although the coal has a relatively low permeability, the postmining spoil will be even less permeable. Even in this area the postmining spoils should be able to provide the small yields required by livestock wells, and therefore the spoil aquifers will support the postmining land use, which is generally rangeland.

Another aspect of spoils hydrology that has been the subject of some concern is the recharge capacity of the postmining spoils. SMCRA performance standards (Section 515(b)(10)(D)) require that the recharge capacity of the mined area must approximate premining conditions. Groundwater recharge is difficult to quantify because it is a function of the spatial and temporal distribution of precipitation, topography-runoff relationships, and the unsaturated and saturated hydraulic properties of a spatially-heterogeneous geologic environment, and because it is derived from three possible sources:

a. lateral recharge from adjacent, unmined strata (coal and overburden),

b. vertical recharge from underlying aquifers, and

c. vertical recharge from surface infiltration.

The Montana DSL (Robert Ringler, 1983) used data presented in the West Decker (Decker Coal Company, 1981 and 1982) and Rosebud (Western Energy Co., 1980 and 1983) permit-application documents and associated reports, together with data collected by the Montana Bureau of Mines and Geology (Van Voast and Hedges, 1975, and Van Voast and others, 1977) to assess spoil recharge at the West Decker and Rosebud Mines. Representative monitoring wells in the coal and spoils aquifers for each mine were selected, and hydrographs utilizing all available water-level data were plotted and analyzed to correlate water-level changes with seasonal fluctuations and mining operations. From these data it was determined that spoils recharge at the West Decker Mine comes mainly from adjacent, unmined coal beds that subcrop beneath the Tongue River Reservoir. A secondary source is underlying, unmined coal beds. Surface infiltration is considered insignificant due to the thickness and fine-grained texture of the spoils. At the Rosebud Mine, recharge is predominantly from adjacent, unmined coals. In localized areas, surface recharge to the spoils is enhanced by thin spoils, coarse-textured spoils, and surface-water bodies.

Where on-site data are not available with which to determine recharge from surface infiltration, a water-budget approach is used. Examples of this analytical technique are given in case studies in Chapter 3 (Sections 3.16 and 3.20).

Investigators in North Dakota utilized selected analyses of stable isotopes of oxygen and hydrogen to evaluate sources of recharge in spoils (Groenewold and others, 1983). The isotopes commonly used to evaluate recharge are oxygen-18 and deuterium. Snow and snowmelt generally have considerably lower oxygen-18 and deuterium values than rain, and evaporation enriches water in these isotopes. Therefore, these isotopes can be used to determine both the precipitation source (rain or snowmelt) and also the topographic source of the infiltrating water, such as sloughs or mine pits where evaporation is significant (Groenewold and others, 1983, p. 113).

An additional isotope of use in evaluating groundwater recharge sources is tritium, the major source of which has been atomic testing carried on since 1950. Tritium data indicate that the source of the water in the basal portion of the spoils at the Center Mine in North Dakota is not from adjacent unmined areas. Thus, the presence of groundwater in the spoils is either due to vertical infiltration through the spoils or lateral inflow from adjacent surface-mine pits. The oxygen-18 and deuterium data suggest snowmelt as the primary precipitation source for most of the groundwater in the spoils and unmined materials and indicate that the water in the spoils has not been affected by evaporation. These data indicate that the mechanism and topographic source of the groundwater in spoils at the Center Mine is vertical infiltration from nonevaporative sites, predominantly during the period of spring snowmelt, rather than lateral inflow from adjacent mine pits. Thus, the recharge mechanism in spoils at the Center Mine is very similar to that of the premining setting (Groenewold and others, 1983).

The studies described above indicate that sources of spoil recharge are site-specific. As described in the following section, there are times when recharge from surface infiltration is undesirable, and, to protect groundwater quality steps may be warranted to limit recharge from this source.

2.4.2.4 Prediction of Postmining Groundwater Quality

Surface coal mining has generated considerable concern and debate regarding its impact on subsurface water, especially on shallow aquifers in the overburden and coal which are used extensively to supply livestock water and occasionally to supply domestic water. In most cases, the resaturated spoils will be able to supply wells with water of sufficient quantity and quality to meet these same needs after mining. In some areas, however, it may be many years after mining and reclamation are complete before the spoils are fully resaturated and groundwater flow patterns are reestablished. Water quality is expected to be degraded in the resaturated spoils, at least until the spoils have been leached by sufficient volumes of water to establish an equilibrium between incoming water and soluble constituents in the spoil material.

In this section analytical techniques used to predict water quality in the resaturated spoils and special reclamation techniques to minimize adverse impacts on the groundwater quality being used or recommended for use are described.

It is well known that the disruption of shales and sandstones by mining exposes fresh mineral surfaces for leaching, and that for a period of time the quality of water that flows through these materials will be influenced. The general geochemical processes that affect groundwater quality after mining include oxidation of mineral matter and organic matter, reaction of carbon dioxide and water to form carbonic acid, dissolution of calcite and dolomite, precipitation and dissolution of gypsum, cation exchange, and sulfate reduction.

Where iron sulfide minerals (pyrite and marcasite) are present in the overburden materials and undergo oxidation, they react with water and oxygen to form iron hydroxide, sulfate ions, and hydrogen ions. This reaction is one of the strongest acid-producing reactions known to occur in natural geologic systems, and is the cause of the acid mine-drainage problem that has been so environmentally damaging in the Appalachian region of the United States (Groenewold and others, 1983). In the west, however, carbonate minerals, calcite and dolomite, constitute a high percentage of the overburden materials. Where these minerals are present they provide a control on pH of the aqueous solution by producing bicarbonate ions. The alkalinity of the water will rise until the water is saturated with respect to the carbonate minerals present. Even though the pH may be kept neutral or slightly basic by the dissolution of carbonates, salinity can increase as the pyrite oxidizes and the carbonates dissolve (Moran and others, 1979).

Where gypsum is present it dissolves readily in water to produce calcium and sulfate ions. Calcite or dolomite dissolution in water in advance of gypsum dissolution will cause the solubility of gypsum to be reduced as a result of the common-ion effect. If the calcium concentration is limited by cation exchange, gypsum solubility will be increased. When calcium enters solution as a result of calcite or dolomite dissolution and sulfate enters solution as a result of pyrite oxidation, and if the water is concentrated to a level at which gypsum supersaturation occurs, gypsum will precipitate from solution. If the overburden material contains appreciable amounts of sodium, then calcium will exchange with the sodium, raising the concentration of dissolved sodium in the water. If carbonate minerals are not sufficient to consume excess acid produced by the above reactions and the pH is lowered, trace elements can be dissolved, creating a potential for groundwater contamination.

In the western United States, the primary groundwater contamination problem associated with surface coal mining is the elevation of total dissolved solids (TDS) levels in spoil groundwaters. The soluble salts observed to be the principal constituents responsible for the elevated TDS levels are the salts of sodium, calcium, magnesium, and sulfate.

There are two general approaches in use today to predict spoil water quality. These approaches are described in Appendix D. One approach involves measuring water-soluble constituents in the spoils, using batch-mixing, saturated paste extracts, or column-leach tests, and relating these values to spoil-water quality at the respective mines. This method assumes that spoil-water quality is largely a function of the readily-soluble constituents in the spoils which are easily leached by groundwater. This spoil water-quality prediction method is the procedure most frequently used in the western United States. Examples of the use of a column-leach study are presented in Appendix D and in Section 3.15.

The second general approach entails a complete understanding of the chemical processes responsible for the evolution of spoil-water quality, and using these processes to calculate the ultimate water quality. Three USGS computer models are being used under this general approach to attempt to understand and predict the evolution of spoil-water quality. Descriptions of these models (WATEQF, BALANCE, and PHREEQE) are provided in Appendix D. NERCO Mining Co. is currently using these models to help explain chemical characteristics of the spoil water at the Dave Johnston Mine in the southern Powder River Basin of Wyoming (Gary Hecox, Hydrologist, NERCO Mining Co., January 10, 1985, personal communication). Using methods described in Appendix D, researchers in North Dakota are also using a comprehensive hydrogeochemical approach to the prediction of spoil-water quality. A significant aspect of their model is that the interpretive framework developed accounts for observed water chemistry in natural overburden as well as in replaced spoils. The North Dakota researchers are convinced that the saturation-paste extract method estimates only short-term spoil-water quality by considering only soluble salts in the overburden and not the long-term salt-generating capacity, which is a function of the abundance of oxidizable pyrite.

All the methods described in Appendix D used to predict spoil-water quality require overburden geochemical data. As indicated in the comparison of requirements of the various states in Table 8, a

Table 8. Comparison of Overburden Chemical Analysis Requirements for the State and Federal Programs Considered in this Investigation

Item	Federal	Colorado	Montana	New Mexico	North Dakota	Wyoming
Drill hole density	not specified	1 hole/640 ac 3 holes minimum (Guideline)	1 hole/40 ac more for dissimilar areas (Guideline)	1 hole/150 ac 3 holes minimum (Guideline)	1 hole/40 ac (Rule 69-05.2-08-05)	1 hole/40 ac (Guideline)
Sample interval	not specified	4 to 10 ft carbonaceous units less than 1 ft thick (Guideline)	not specified	2 to 10 ft (Guideline)	5 ft (Rule 69-05.2-08-05)	5 to 10 ft (Guideline)
Identify acid- and toxic-forming strata	yes (30CFR 780.22)	yes (Regulation 2.04.6)	yes (Regulation 26.4.304)	yes (Regulation 8-14)	yes (Rule 69-05.2-08-05)	yes (Regulations, ch. 11, Sec. A.3)
Required analyses	not specified	SAR, Se, B, pyritic S, SO_4, organic S, Mo, Pb, As, Cd, Fe, Mn, Cu, Hg, Zn (Guideline)	ESP, SAR, Se, B, ABP (if requested), Mo (Guideline)	SAR, SE, B, ABP, Al, As, Ba, Cd, Cr, Co, Cu, Cn, Fe, Pb, Hg, Mo, Ni, Ag, U, V, Zn, Ra-226, Ra-228, (Guideline)	SAR (Rule 69-05.2-08-05)	SAR, Se, B, ABP, TOC, As, Mo (Guideline)

Taken in part from Walsh, 1985.

disparity of opinions exists on the appropriate density of overburden samples required. Overburden sampling in Montana, Wyoming, and North Dakota is required at a density of one hole per 40 acres. New Mexico requires one hole per 150 acres, while Colorado requires one hole per square mile. A disparity also exists in the number of chemical analyses required (Table 8). A recommendation was made by the Department of the Interior, Bureau of Land Management (1977), for limited sampling and analysis of overburden for studies of reclamation potential. Justification was that the rock material is sufficiently homogeneous and the concentrations of harmful elements sufficiently low that the large amount of money required for intensive sampling is not justified. In contrast, it was concluded from a study by Dollhopf and others (1981) that drilling and sampling would be required on a 43-meter grid to provide 90-percent certainty that all overburden inhibitory zones would be identified at a mine site in Montana. The ability to characterize unsuitable overburden with drill holes 600 to 1500 meters apart, as recommended by the states, has an accuracy of only 45 to 60 percent for this particular mine site. Similar determinations for other mine sites have not been made. Dollhopf and others acknowledge that intensive sampling could become prohibitively expensive. They suggest a two-phase approach that begins with a wide grid spacing (i.e., 600 meters). Following the initial overburden analyses, only the parameters that occurred above or near inhibitory levels would be considered in the second phase of sampling. The second intensive drilling and sampling program would be designed to attain a characterization accuracy of 80 to 90 percent of a chemical migration inhibitory zone. To attain that accuracy, a 60-meter drilling grid would be necessary. Another way to save drilling costs and yet maintain the characterization accuracy would be to couple the overburden sampling with the drilling of the highwall for blasting. This suggestion has problems because frequently insufficient time is available between the drilling, blasting, and removal of the overburden to allow the mine operator to react to the results of the geochemical analyses. Drilling and sampling of the mine highwall may be best utilized to guide subsequent drilling (back from the highwall) and delineation of potential inhibitory zones (Kaman Tempo, 1983).

The foregoing discussion, together with information presented in Appendix D, shows that special handling of selected overburden materials during mining can affect postmining spoil-water quality. Dollhopf and others (1981) conclude that the ideal place for burial of saline materials is beneath a hill where runoff is maximized and surface recharge is minimized. Opportunities for placement of such materials, and the ability to do so with conventional mining techniques, is limited, particularly in areas of thin overburden where the postmining water table will be within several meters of the land surface. Other researchers have shown that the worst impacts on spoil-water quality would result from placement of unoxidized sodic and sulfide-rich sediments near the surface but above the water table, where infiltrating surface water could contact these sediments as it percolates to the water table. According to these researchers, placement of these materials below the water table may result in short-term water quality degradation due to solution of salts, but over the long term will prevent oxidation of the sodic and sulfide-rich sediments and water quality will improve after initial flushing of soluble salts (Groenewold and others, 1983). This implies that where it is not possible to place unsuitable overburden materials beneath a hill, where oxidation and surface recharge will be minimal, it may be preferable to place them below the postmining water table.

When other wastes are placed within the spoils, such as fly ash or scrubber waste from power plants, concerns over water quality are increased. Some constituents contained in the coal, notably metals, can be concentrated in the ash and under certain conditions could be mobilized by groundwater. The Wyodak Station near Gillette disposes of fly ash within the mine spoils at the Wyodak Mine. Due to thin overburden conditions it is necessary to dispose of this material beneath the postmining water table. The Wyoming Department of Environmental Quality requires that the ash material be encapsulated in compacted clay cells to minimize impacts to groundwater quality. Chemical analysis of the ash, column-leaching studies of the ash and ash-overburden mixtures (Western Water Consultants, Inc. 1981), and accelerated-aging studies of the compacted clay liners subjected to leachate from the ash (Western Water Consultants, Inc., 1985) were required to document that the selected disposal method would minimize groundwater-quality degradation. As described in Section 3.16 in Chapter 3, the Colorado Mined Land Reclamation Board has required that utility wastes be disposed of above the postmining water table at a surface coal mine in northwestern Colorado.

A coal mine in New Mexico is also disposing of powerplant fly ash and bottom ash from centrifuge sludge in the mine backfill. The analytical techniques used to evaluate potential impacts to groundwater quality at this site are also discussed in a case study in Chapter 3 (Section 3.18).

2.4.3 Evaluation Criteria for Success of Groundwater Restoration

Bond-release criteria for groundwater restoration are summarized by state in Table 5. These criteria are vaguely keyed to whether or not pollution of subsurface water is occurring. However, "pollution" in this context is not defined quantitatively in any state. There are no established numerical quality standards that must be met by postmining groundwater to determine success of restoration efforts. Neither are there any established standards for evaluation of spoil aquifer hydraulics or recharge rates. It may not be possible or reasonable to establish such standards due to imprecise methods available with which to predict postmining water quality and the time it will take in some areas for the spoils to saturate after mining. Current evaluation criteria stem mainly from the SMCRA performance standard (Section 515(b)(10)) which requires the operator to "minimize" the disturbances to the quality and quantity of water in the groundwater system both during and after mining. Due to the lack of numerical standards, groundwater quality impacts are generally analyzed with respect to use-suitability criteria (refer to Table 1). For example, the spoil waters are examined with respect to their suitability for uses for which groundwaters in the area were suitable prior to mining. As shown in the preceding discussion, postmining spoil-water quality may be variable for some time following mining. Therefore it is not certain when any evaluation criteria that are developed should be applied.

Spoil-aquifer hydraulic characteristics are generally evaluated by determining whether the spoils will permit reestablishment of premining groundwater flow patterns and whether they will provide water to wells in sufficient amounts to meet the uses met by the premining coal and overburden aquifers. Since these uses were generally livestock and domestic wells, small well yields (less than 5 gpm) are adequate.

Mine operators must apply for permit renewals in 5-year intervals. If monitoring of spoil-water quality or aquifer testing of the spoils indicates that problems are developing, corrective measures can be worked out during review of permit-renewal applications (Rick Lawton, Soil Scientist, Wyoming Department of Environmental Quality, January 28, 1985, personal communication). Monitoring requirements for restored aquifers are not specified by regulations. Normally, a monitoring plan is worked out between the applicant and the regulatory authority during permit-application review. Monitoring programs generally consist of installation of monitor wells, quarterly or semiannual monitoring for selected chemical characteristics, and quarterly or semiannual static water-level measurements. The regulatory authority usually encourages that some of the spoil monitor wells be installed in pairs so that multiple-well tests can be conducted to determine transmissivity and storage coefficient of the spoils aquifer. There are no general standards for number and spacing of spoil monitor wells.

2.5 Alluvial Valley Floor Hydrology

2.5.1 Data

SMCRA (Section 510(b)(5)) requires that surface coal mine operations in the western United States cannot be permitted if they will interrupt, discontinue or preclude farming on alluvial valley floors (AVFs) that are irrigated or naturally subirrigated unless the acreage is small. Also, the mining operation cannot materially damage the quantity or quality of water in surface or underground water systems that supply valley floors that would otherwise be prohibited from mining. Where mining is not prohibited on an AVF because the acreage is small or the land is undeveloped rangeland, special reclamation standards are required to preserve or restore the essential hydrologic functions of the AVF (SMCRA, Section 515(b)(10)(F)).

In considering an AVF, the applicant must answer the following questions:

a. Are there AVFs in or near the proposed permit area?
b. Are any of those AVFs subject to prohibition from mining?
c. What will be the effect of proposed mining on the AVF?
d. Can the essential hydrologic functions (EHFs) of the AVF be restored?

In order to answer these questions, specific data and analyses are needed. The AVF regulatory process is summarized in the flow chart of Figure 2. The prohibition questions are related to land use and agricultural production and are not specifically hydrologic issues. This section describes the data used to identify essential hydrologic functions of AVFs where mining is not prohibited and methods used to restore the EHFs of AVFs that will be mined.

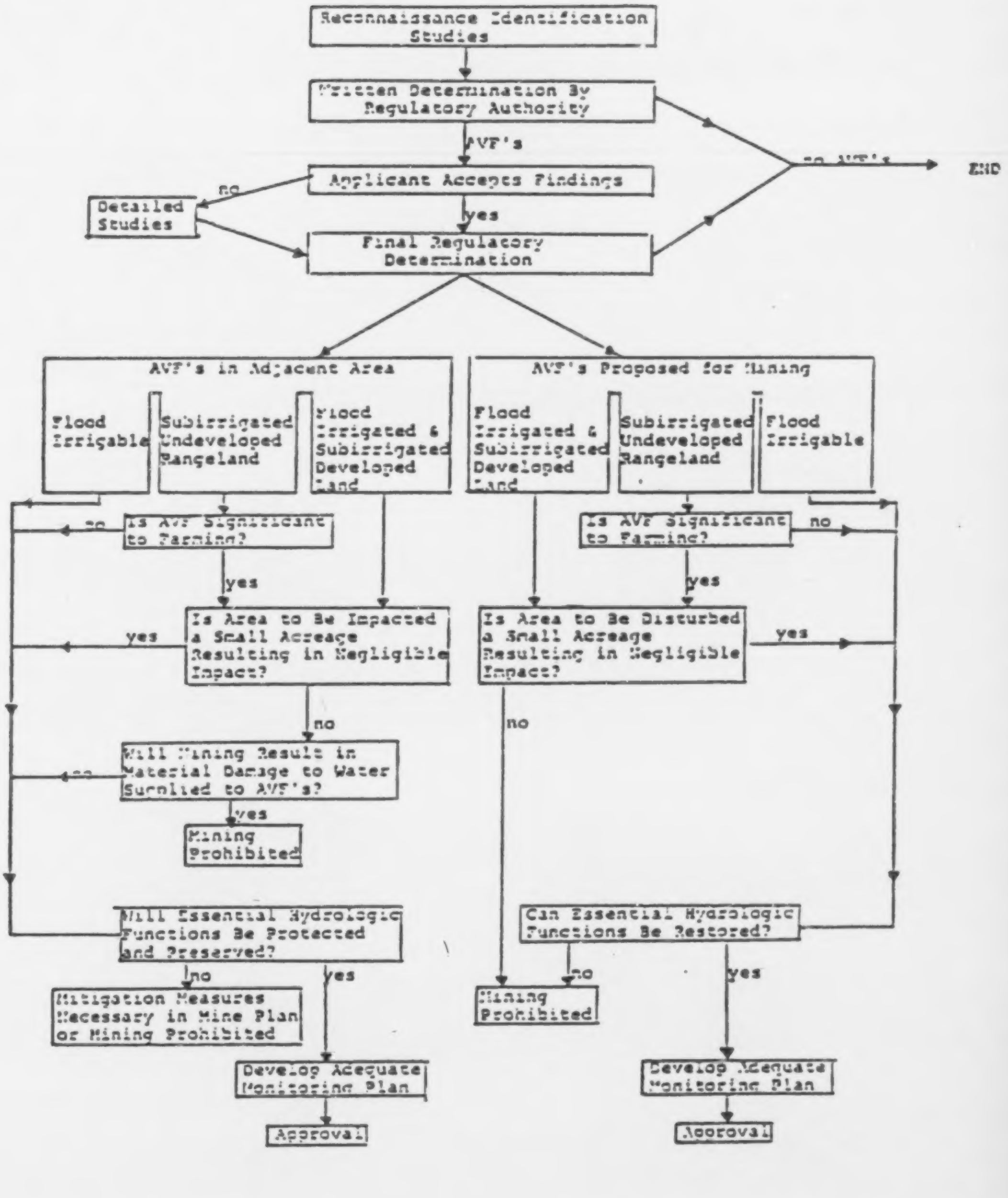
Reconnaissance Identification Studies
Written Determination By Regulatory Authority
AVF's
no AVF's
END
Applicant Accepts Findings
no
Detailed Studies
yes
Final Regulatory Determination
AVF's in Adjacent Area
Flood Irrigable
Subirrigated Undeveloped Rangeland
Flood Irrigated & Subirrigated Developed Land
AVF's Proposed for Mining
Flood Irrigated & Subirrigated Developed Land
Subirrigated Undeveloped Rangeland
Flood Irrigable
no
Is AVF Significant to Farming?
yes
Is AVF Significant to Farming?
no
yes
yes
Is Area to Be Impacted a Small Acreage Resulting in Negligible Impact?
Is Area to Be Disturbed a Small Acreage Resulting in Negligible Impact?
yes
no
no
no
Will Mining Result in Material Damage to Water Supplied to AVF's?
yes
Mining Prohibited
Will Essential Hydrologic Functions Be Protected and Preserved?
no
yes
Mitigation Measures Necessary in Mine Plan or Mining Prohibited
Develop Adequate Monitoring Plan
Approval
Can Essential Hydrologic Functions Be Restored?
no
yes
Mining Prohibited
Develop Adequate Monitoring Plan
Approval

Figure 2. Flowchart of Alluvial Valley Floor Regulatory Process (OSM, 1983)

Identification of an AVF requires an integration of geology, hydrology, and agricultural land use. AVF investigations are highly site-specific, and relatively little use can be made of regional data. Often a preliminary estimate of the extent of streamlaid deposits can be obtained from the U.S. Geologic Survey, which in its miscellaneous field investigations program has published preliminary surficial geologic maps of most of the coal-mining areas in the west at a scale of 1:24,000. More detailed surficial geologic maps are prepared by permit applicants from larger-scale topographic maps, stereo-paired aerial photos, and site inspections to refine the estimate of areal extent of streamlaid deposits. After the areal extent is delineated, land use is determined to see if the mining prohibition would apply. If agreement between the applicant and the regulatory authority can be reached at this time, the decision as to whether or not the area can be mined can be obtained without the expense of detailed hydrologic investigations.

If it is determined that the area can be mined, detailed studies are conducted to identify the EHFs and provide a plan for their restoration. Many of these studies are similar to those previously described for surface-water and groundwater investigations. Streamflow characteristics are determined from existing regional or site-specific streamflow data, rainfall-runoff modeling or the applicants' own monitoring program. Wells are installed to determine the depth and saturated thickness of the alluvial aquifer. Pump tests are conducted to quantify the aquifer hydraulic characteristics (transmissivity and storage coefficient). In addition to these studies, special studies are conducted to collect data on the hydrologic functions unique to alluvial valley floors. These functions include the collection, storage and regulation of water flow which results in water being usefully available from the stream or alluvial aquifer for agricultural purposes. Special functions of AVFs that must be determined include the interchange of water between the surface stream and the alluvial aquifer and between the alluvial aquifer and bedrock aquifers; the depth to the alluvial water table and the soil texture above the water table; and water quality in the stream and alluvium.

The following is a generalized outline of data requirements that have been successfully used for a determination of essential hydrologic functions of a typical AVF (The Carter Mining Company, 1984).

a. Determination of site geomorphology and watershed characteristics, including drainage-basin parameters, streamflow characteristics and channel and flood-plain geometry,

b. Determination of hydrogeological characteristics of the AVF, including thickness, lithology and areal extent of alluvial deposits, aquifer hydraulic characteristics including saturated thickness, transmissivity, storativity, and flow rates and directions of flow in the alluvial aquifer and in hydraulically-connected bedrock aquifers,

c. Determination of water-quality characteristics of the surface water and alluvial and bedrock aquifers, and

d. Determination of presence and extent of subirrigation, including installation of water-level recorders on alluvial wells to determine diurnal water-level fluctuations. This information, together with information on porosity and areal extent of the alluvial aquifer, can be used to quantify the amount of groundwater transpired by plants during daylight hours.

When the database indicated above is assembled, a hydrologic budget of the AVF can be prepared. Typically, a hydrologic budget analysis will be designed to solve the following equation:

$$Q_{si} + Q_{or} + Q_{ai} + Q_{bi} = Q_{so} + Q_{ao} + ET + S$$

where:

Q_{si} = streamflow into the reach

Q_{or} = overland runoff within the reach

Q_{bi} = recharge from bedrock to alluvium over the reach

Q_{ai} = alluvial underflow into the reach

Q_{so} = streamflow out of the reach

Q_{ao} = alluvial underflow out of the reach

ET = water consumed within the reach by evapotranspiration

S = change in storage

Units in the preceding equation are expressed in consistent terms of volume (i.e., acre-feet, cubic meters, etc.).

In the preceding equation Q_{si} and Q_{so} can best be measured in a seepage run (instantaneous measurement of streamflow at numerous sites). Q_{ai} and Q_{ao} are determined from a flow-net analysis of the alluvial aquifer using aquifer parameters determined from pump tests and water-level measurements in alluvial wells made during the seepage run. One seepage run is made during a dry period when Q_{or} is zero. S, the change in storage in the reach, were determined from water-level changes in alluvial wells during the seepage run. Thus only two terms are unknown, Q_{bi} and ET. A seepage run conducted during the non-growing season, when ET is zero, enables determination of the bedrock accretion (or loss). This is generally assumed to be a constant, leaving only the ET value to be determined from a second seepage run conducted during the growing season. Having thus determined the hydrologic balance for the AVF, impacts during mining can be determined and plans can be made to restore the EHF during mining and reclamation.

Using the hydrologic budget equation, if bedrock aquifers are dewatered in the vicinity of the AVF causing the term Q_{bi} to become zero, material damage to the AVF can be quantified. In the context of AVFs, "material damage" is defined by regulations as changes in the quality or quantity of the water supply to any portion of the AVF where such changes are caused by surface coal mining and reclamation operations and result in changes that significantly and adversely affect the composition, diversity, or productivity of vegetation dependent on subirrigation, or which result in changes that would limit the adequacy of the water for flood irrigation.

The preceding example illustrates the importance of temporal distribution of AVF hydrologic data. Seepage runs must be made over a sufficiently short period of time that the measurements can be assumed to have been made instantaneously. Some measurements must be made during the non-growing season and some must be made when evapotranspirational processes are active. Measurements of diurnal fluctuations in water-table elevations are required to quantify evapotranspiration. Uses of these data are described in the following section.

2.5.2 Analytical Techniques for AVF Restoration

As yet, no designated AVF has been mined and successfully reclaimed (OSM, 1983). However, several plans for reclamation have been proposed in approved mining permits. Examples of AVF restoration plans are presented in the case studies of Chapter 3 (refer to Sections 3.10 and 3.14).

In planning for the restoration of AVFs, attention is focused on the following items:

a. Channel and flood-plain geometry and erosional stability, and
b. Alluvial aquifer depth, thickness, and water-storing and transmitting capabilities.

Principles used in the design of the restored channel and flood-plain are basically the same as those described in Section 2.3.2.4. Topography adjacent to the AVF after mining is typically flatter than the premining land forms, increasing its value for irrigation.

The simplest plan for restoration of an alluvial aquifer is to salvage and replace alluvial materials present in the undisturbed valley (see Section 3.14, Chapter 3). Typically, these alluvial materials grade from very fine-grained deposits near the surface to coarser-grained sands and gravels at the base of the deposit. Often there are fine-grained sequences mixed within other layers. Due to mixing, an inevitable consequence of mining, salvage and replacement of these materials may not replace the premining hydraulic properties of the material. Also, chemical properties of some alluvial materials make them undesirable for aquifer reconstruction. Other materials such as sandy overburden may make better material for alluvial aquifer reconstruction. Most AVF restoration plans provide for the construction of a compacted layer beneath the replaced alluvium. This will help to minimize loss of streamflow into the spoils and, since it may be many years before water levels in the spoils recover, should help to speed up restoration of the EHF of the alluvial system by making its restoration relatively independent of that of the surrounding spoils (see Case Study 3.10, Chapter 3).

2.5.3 Evaluation Criteria for Success of AVF Restoration

As opposed to surface-water and groundwater restoration, regulatory bond-release criteria for the success of AVF restoration (refer to Table 5) are somewhat more specific. Federal regulations (30CFR 807.12, since rescinded) and corresponding regulations in Colorado, Montana and North Dakota require that the bond shall not be released until the reestablishment of essential hydrologic functions and premining agricultural productivity on alluvial valley floors has been achieved. Restoration plans are detailed in the permit-application document, and each operator is required to conduct his activities in accordance with his approved mine plan. Performance standards (SMCRA, Section 515(b)(2)) require the operator to restore the disturbed land to a condition capable of supporting the uses which it was capable of supporting prior to mining. By definition, an AVF must be capable of supporting subirrigation or flood irrigation agricultural activities. The characteristics that support irrigation are designated as EHF, and thus the criteria for evaluation are more clearly defined. Monitoring programs that essentially duplicate those used to define the premining EHF can be used after mining to determine whether these functions are restored. The time frame within which the bond-release criteria listed in Table 5 must be applied is not specified in any state, and as with other surface and groundwater restoration measures it may be many years after reclamation activities are complete before the hydrologic system achieves steady-state conditions. In view of the time frames estimated in some areas for the reestablishment of groundwater levels (refer to Section 2.4.2.3) it is conceivable that a mine operator could develop an adequate plan for AVF restoration, implement that plan and complete the entire reclamation plan, and yet bond release could be withheld for an undetermined amount of time under the regulations listed in Table 5. The mine described in Section 3.10 is aware of this issue and has taken special measures to hasten the resumption of subirrigation on the restored AVF.

3.0 CASE STUDIES

This chapter presents case-study analyses of 20 surface coal mines in the five western states addressed in this investigation. The mines were selected, primarily at the suggestion of regulatory authority personnel from the respective states, to illustrate specific examples of the utilization of data, analytical techniques and/or evaluation criteria described in Chapter 2. Information presented in the case studies was taken from mine permit-application documents, interviews with personnel from regulatory authorities, interviews with mine operators, and review of State and Federal decision documents. A summary of the case studies is provided in Table 9. The names of the mines are not provided at the request of OTA.

3.1 Case Study A

3.1.1 Focus

This first case study is of a mine located in the Missouri River Breaks of North Dakota and is used to illustrate data requirements, analytical techniques, and evaluation criteria for the restoration of a surface-drainage system in an area of relatively steep slopes.

3.1.2 Description of Mine and Hydrologic Setting

The mine is located near the west bank of the Missouri River and has been in operation since 1965. The permit area contains about 5,600 acres of which about 3,000 acres involve Federal coal leases. Essentially all of the 2 to 4 million tons of lignite produced each year

Table 9. Summary of Case Studies

Case Study	State	Focus	Baseline Data Presented	Analytical Techniques Used	Evaluation Criteria	Issues
A	North Dakota	Surface-water restoration.	Quantitative analysis of geomorphology of premining drainage basins.	Longitudinal profiles of reclaimed channels purported to indicate stability. Monitoring locations selected to include disturbed areas (impact points).	Surface-water monitoring program.	Inadequate use of baseline data to design postmining drainage system. No specific criteria established for use of monitoring data in evaluation of surface-water restoration.
B	North Dakota	Prediction of groundwater impacts and spoil-water quality.	Static water-level data from monitor wells. Aquifer hydraulic parameters. Water-quality data from coal and sub-coal monitor wells. Reference to spoil-water quality data from other mines.	Static water-level data used to construct potentiometric-surface maps which in turn were extrapolated to predict future drawdowns. Data from other North Dakota mine extrapolated to predict spoil-aquifer hydraulic and water-quality characteristics.	Groundwater monitoring program.	No numerical criteria for determination of success of groundwater quality restoration. Possible discrepancy between length of time for bond release and length of time for restoration of groundwater flow indicates need for method to evaluate probability of success of groundwater restoration.
C	North Dakota	Restoration of wetlands.	Water quality, including temporal variation. Geometry of wetlands and their drainage areas. Soils, vegetation and drainage-basin parameters for input into rainfall-runoff model and water-balance studies.	Computerized rainfall-runoff model (TR-20) Design of wetlands to simulate natural wetlands.	Comprehensive evaluation criteria being developed by specially-selected advisory committee.	Innovative technology being developed for wetland restoration. Evaluation criteria for wetland restoration being developed as restoration proceeds. No alternative plan if wetland restoration is unsuccessful.
D	North Dakota	Efficiency of permit process for new mines where there are no outstanding hydrologic features and where the application was prepared under current regulatory framework.	Reliance on other studies in vicinity.	Handbook used to estimate premining and postmining runoff. Reference to literature to predict spoil-water quality.	Surface-water and groundwater monitoring program.	Permitting efficiency may be promoted by expanding base of knowledge of hydrologic restoration, requiring less-detailed studies in any one permit application document
		Evolution of hydrologic restoration technology.				Lack of attention to surface-water restoration.
E	Montana	State-of-the-art CHIA, AVF study, and PHC determination.	Extensive use of regional data as well as thorough data-collection by the applicant.	Flow nets. Hydrologic budget for AVF. Regional flood-estimating techniques. SCS triangular hydrograph rainfall-runoff model. One-dimensional and Theis methods for drawdowns. Darcy equation for pit inflows. Literature plus site-specific overburden analysis used to predict spoil-aquifer hydraulic characteristics. Literature plus saturated-paste extract data to predict spoil-aquifer water quality. Universal Soil Loss Equation for erosion estimates. Hydraulic and geomorphic approach to channel design. Mass-balance equations for water-quality impacts.	Comprehensive analyses provided for PHC and CHIA. Surface-water and groundwater monitoring program.	Uncertainties exist eve with state-of-the-art analytical techniques, including: 1. Time required for groundwater restoration, 2. Cumulative impacts on groundwater quality, 3. Temporal variations in spoil--water quality and associated uncertainties as to when and how to apply evaluation criteria, and 4. No definitive plans to evaluate and then refine predictive techniques. Variations in level of detail required by different state regulatory authorities.

Table 9. Summary of Case Studies (Continued)

Case Study	State	Focus	Baseline Data Presented	Analytical Techniques Used	Evaluation Criteria	Issues
F	Montana	This mine has been the site where much of the data and analytical techniques concerning groundwater impacts of mining were developed.	Extensive site-specific and regional groundwater database developed by two research agencies.	Primarily analysis of empirical data.	Surface-water and groundwater monitoring program.	Special handling of overburden required to protect water quality, but no numerical metho established to evaluate the results obtained.
G	Montana	Management and utilization of a large and expanding hydrologic database.	Extensive site-specific and regional hydrologic database and reference library.	Regional flood studies and SCS triangular hydrograph method for peak flows. Restored channels designed with uniform-flow equation. Groundwater flow computed with Darcy equation using observed gradients and aquifer hydraulic data from pump tests. Reference to reports by others, some of which were based on work at this mine, for spoil-aquifer hydraulic and water-quality data.	Surface-water and groundwater monitoring program.	How much monitoring is necessary to evaluate the probability of reclamation success? Programs needed to manage and evaluate large and growing databases from several mines.
H	Montana	Hydrologic issues associated with a mine situated adjacent to a major river and irrigation reservoir.	Good groundwater database developed by operator and a research agency. Geomorphic baseline presented for premining drainage basins.	Darcy equation and flow net to estimate pit inflows. SCS triangular hydrograph method for flood flows.	Surface-water and groundwater monitoring program and comparison with data from undisturbed areas.	No plan to use monitoring data to evaluate success of hydrologic restoration. No surface-water restoration design. Apparent redundancy in data-collection. When will evaluation criteria be applied, considering a bond-evaluation period of 10 years and time for groundwater reestablishment of 100 years.
I	Wyoming	Alternative sediment control. Experimental practice procedure.	Limited baseline TSS data; watershed and precipitation data for rainfall-runoff and sediment-response modeling.	SEDIMOT-II computer model. State-of-the-art streamflow sampling. Rigorous data analysis.	Comprehensive data collection and analysis to determine success of alternative sediment-control practice and comply with experimental-practice requirements.	Point-source effluent standard vs nondegradation of water quality. Good-quality monitoring when specific evaluatio criteria are applied.
J	Wyoming	Identification of AVF EHF and plans for restoration of AVF.	Aerial photos, topographic maps, test holes and backhoe pits, review of water rights, surface and groundwater quality and quantity.	Well-field simulation to compute alluvial drawdowns. Replacement of alluvial aquifer.	Detailed AVF monitoring programs used to design restoration program and evaluate restoration of EHF.	Good-quality design and monitoring when specifi evaluation criteria are applied. Uncertainties as to ti necessary to restore EHF.
K	Wyoming	Innovative surface-water restoration.	Topographic maps to document locations of premining channels. Lack of baseline streamflow quality and quantity data.	Grade channel areas to desired slope and then let channels form on their own through erosion and deposition (since rescinded).	Lacking.	Lack of evaluation criteria for surface-water restoration. Inconsistencies in application of regulatory program concerning monitoring and alternative sediment control.
L	Wyoming	Use of digital computer model to predict groundwater impacts.	Data from over 50 wells. Use of data from adjacent mines.	Flow nets to approximate directions and rates of groundwater flow. Prickett-Lonnquist model to simulate drawdowns and postmining conditions for one mine and all mines in general area.	Extensive analyses to evaluate groundwater impacts and restoration through modeling. No criteria for evaluation of successful restoration.	Advantages of computer simulations over manual calculations. Points out uncertaintie as to when groundwater restoration criteria ca practically be applied.

Table 9. Summary of Case Studies (Continued)

Case Study	State	Focus	Baseline Data Presented	Analytical Techniques Used	Evaluation Criteria	Issues
M	Wyoming	Surface-water monitoring on ephemeral streams. Carbonaceous overburden.	34 crest-stage gage pairs. 2 USGS stations. 3 recording stations with automatic samplers. Identification of toxic and acid-forming overburden in accordance with state guidelines (41 drill holes, 757 samples for chemical analysis).	TR-20 computer model. Postmining channels designed with hydraulic and geomorphic principles. Comparison of analytical techniques to determine ABP of overburden.	Evaluation of surface-water restoration by comparison of post-mining drainage design with baseline studies. Groundwater monitoring.	Perfunctory data collection and reduction. Infrequency and variability of flow on ephemeral streams makes it difficult to evaluate reclamation from streamflow monitoring. Good use of monitoring and baseline data to evaluate groundwater restoration.
N	Wyoming	Efficiency of permitting for new mine.	Geomorphic data on premining drainage system. Use of regional data. Extensive groundwater and geologic baseline studies. 63 monitor wells.	Postmining surface drainages designed with hydraulic and geomorphic principles. Batch-mixing test to estimate spoil-water quality. Theis equations to predict drawdowns.	Evaluation of surface-water restoration by comparison of postmining drainage design with baseline studies. Groundwater monitoring and comparison with water quality predicted through column-leach tests.	Regulatory guidelines promote permitting efficiency and enhance probability of successful hydrologic restoration. Problems in evaluating hydrologic restoration within bond-release period.
O	Colorado	Groundwater restoration in an area where important, perennial streams are subject to cumulative hydrologic impacts.	USGS and USDA streamflow data and 4 stream gages operated by applicant. Groundwater data from 47 test wells and 10 monitor wells. 4 pump tests. Good geologic baseline inventory. Chemical analysis on 156 overburden samples from 29 drill holes.	Theis equations for pit inflow. Drawdowns computed from Jacob-Lohman equations. Flow-net analysis for recharge study. Column-leaching studies for predicting postmining groundwater quality. Two-dimensional solute-transport equation.	Monitoring to verify modeled predictions.	Conflict between time for groundwater quality to stabilize and duration of bond-release evaluation.
P	Colorado	Groundwater impacts from burial of power-plant wastes in backfill.	Analysis of soluble contaminants in wastes. Potentiometric-surface data from monitor wells.	Water balance to estimate recharge.	Monitoring to verify modeled predictions.	Lack of information regarding surface recharge.
Q	Colorado	Experimental practice.	Drainage-area data from topographic maps. Precipitation data from NOAA Atlas.	SCS triangular hydrograph method to compute rainfall runoff. Manning equation to design permanent channel.	Lack of hydrologic evaluation criteria and criteria to evaluate experimental practice provisions.	Long-term erosional stability in question. Intent of experimental practice provision ignored.
R	New Mexico	Permanent diversion. Groundwater impacts from burial of power-plant wastes in backfill.	Baseline surface-water data from 10 stations on and near the mine. Channel bed and bank samples, surveyed channel cross sections, watershed and precipitation data for input into SCS triangular hydrograph technique.	SCS triangular hydrograph method to compute rainfall runoff Column-leaching studies. Solute-transport model.	Monitoring of erosional stability through channel surveys.	No surface-water restoration plan except design of permanent diversion around the mine area.
S	New Mexico	New mine--examines evolution of hydrologic restoration technologies with time.	Pump tests to determine premining aquifer characteristics.	Regional flood estimating technique. Computer model to analyze groundwater impacts.	Comprehensive erosion-monitoring program to evaluate surface-water restoration. Groundwater monitoring.	Evidence that reclamation technologies are evolving with time. Well-planned surface-water and erosion monitoring program to provide data for evaluation of reclamation success.
T	New Mexico	Permitting efficiency and reclamation success for a small mine with no outstanding hydrologic features.	Pump tests to determine premining aquifer characteristics. Lack of baseline streamflow quantity and quality data.	Universal Soil Loss Equation (USLE) used to determine erodibility. Recharge potential determined using water balance.	Lacking	Long-term stability of surface-water drainage system in question. Premining erodibility study conducted but no postmining studies available.

is utilized by the mine-mouth power plant. Mining is done by both dragline and truck and shovel methods.

The climate of the region is a semi-arid continental type with temperatures ranging from -30°F to over 100°F. The mean annual precipitation is approximately 16 inches, nearly half of which falls during the period from April through September.

The general mine area is drained by eleven small drainages tributary to the Missouri River. Relief within the small basins ranges upward to over 240 feet, and natural channel slopes vary from less than 0.5 to over 2.2 percent. There are many springs and seep sites within the permit area. The primary sources of the groundwater that supplies these springs and seeps are the lignite and clinker beds.

3.1.3 Presentation of Case Study

3.1.3.1 Baseline Data

Baseline surface-water data were provided in the permit application to help characterize streams as ephemeral or intermittent and to provide relationships between stream discharge and water quality. Data presented included USGS data from an existing station on the main intermittent stream channel in the permit area and data collected by the applicant for other sites, consisting of miscellaneous water-quality sampling sites at which stream discharges were estimated during sample collection. As described later, the applicant committed in the application to the establishment of five additional surface-water monitoring stations. The application also presented results of a detailed inventory of springs and seeps within the general area in

1979-1980 wherein flow rates were measured and water sources were determined.

In addition to the surface-water quantity and quality data described above, the application contained a brief quantitative analysis of the premining drainage basins. This consisted of a topographic map on which basins and channels were located and a determination of the following geomorphic parameters for premining drainage basins: basin size, shape, form factor, stream length, and channel slope. Longitudinal profiles of premining channels were also presented.

3.1.3.2 Analytical Techniques

Analytical techniques used to design the restored surface-drainage system were not discussed in the application document. The premining drainage basin parameters were used only to design a surface-water quantity and quality monitoring program. Using geomorphic criteria to locate monitoring stations, the applicant was able to reduce the number of required monitoring stations by making the assumption that basins with similar dimensional properties would respond similarly to mining impacts.

A postmining topographic map showing the locations of reclaimed channels was presented in the application. The applicant prepared longitudinal profiles of the restored channels from the postmining topographic map and compared them with the premining profiles. This was apparently a perfunctory exercise since the postmining profiles showed steeper slopes, more variable slopes, and a lack of upward concavity. No hydraulic design of the restored channels was presented in the application document.

3.1.3.3 Monitoring and Reporting

A surface-water monitoring plan for the mine was developed that includes six surface-water monitoring sites, two of which are equipped with continuous water-level recorders, and ten springs. One of the six surface-water sites is not accessible under all climatic conditions. A bubble-servomanometer gaging facility was installed at this location. Records are not available for two of the sites; however, an additional continuous recording station is planned for one of the sites in the future. At the other site, the landowner refused to grant permission to install a recording station.

Gage-height records are obtained at the remaining four surface-water sites by systematic observation of vertical staff and crest-stage gages located within surveyed approach sections to culvert structures. Readings of vertical staff gages were intensified during the first year of operation to observe runoff from spring snowmelt and thunderstorm events. A hydrologic technician is employed at the mine site to insure the timely acquisition of stage data from these nonrecording stations. Crest-stage gages at these locations are operated with the intent of defining peak discharge rates associated with the various seasonal runoff occurrences, rather than simply the maximum annual peak flow. According to the application, flow measurements will be performed at these locations to verify the developed stage-discharge relationships.

Data from both recording and non-recording gaging stations were to be studied, along with spring-discharge data and the results of streamflow observations, to develop an ephemeral, intermittent, or perennial classification for each stream channel within the permit and adjacent areas. This information was to be submitted to the NDPSC upon completion.

Quarterly reports to be submitted to the PSC will include streamflow and water-quality data recorded during the quarter. Annual reports to be submitted to the PSC will include discharge and water-quality data for springs.

3.1.3.4 Evaluation Criteria

The application contained no design criteria for the restored surface-drainage system; there also are no criteria for the evaluation of the success of surface-water reclamation. In the lengthy discussion of the proposed surface-water monitoring program, it is emphasized that station locations were selected in part so that the drainage areas above these locations would include "impact points", or points located downstream from all possible areas of disturbance. The implication is that the surface-water quality and quantity measurements made at these stations are all that will be required to provide evaluation data. However, no discussion was included as to exactly how water quality and quantity data obtained from the station would be used to evaluate the success of surface-water restoration.

3.1.4 Identification of Issues

The description of the premining drainage system presented in the permit application consisted of premining topographic maps and a determination of certain premining drainage basin parameters, including basin size, shape, form factor, stream length and channel slope.

However, these baseline data were not used to design postmining drainage basins or reclaimed channels.

Information provided in the application regarding the postmining drainage system consisted simply of a postmining topographic map and longitudinal profiles of restored channels. No postmining drainage basin characteristics, design flood flows, or hydraulic designs of channels and flood plains were presented. The postmining longitudinal profiles show channel slopes steeper than premining slopes and a general lack of upward concavity, indicating that the data for the postmining drainage system were not critically evaluated.

The applicant has designed and implemented a surface-water monitoring program and a schedule for reporting the data to the regulatory authority. However, there is no clear description of how the data from the monitoring program will be used to evaluate success or failure of the surface-water restoration plan.

3.2 Case Study B

3.2.1 Focus

This case study illustrates the data and analytical techniques used to predict spoil-aquifer water-quality characteristics and the impact of mining on the groundwater system.

3.2.2 Description of Mine and Hydrologic Setting

This mine is a surface coal mine operating on private surface lands and mining both fee and Federal coal. Coal is removed from each of four open pits and delivered by haul trucks to the tipple where it is crushed and blended. It is then transported in unit trains approximately 300 miles to a power plant.

The production history at the mine ranges from 5,500 tons per year during its inception in 1946 to approximately three million tons per year in 1980. Production is planned to continue at three million tons annually for the next twenty-five years. Approximately seventy-five million tons of lignite will be mined during the life of the mine.

The mine-permit area is located on the southern flank of the Williston Basin. Groundwater occurrence in southwestern North Dakota is categorized into two general groups, shallow aquifers and deep aquifers. Shallow aquifers include sandstones and lignites. Recharge to these aquifers is by surface infiltration in upland areas. The deep artesian aquifers below mining operations are sandstones recharged primarily through outcrops in the Black Hills region of South Dakota and contain large quantities of relatively poor-quality water.

The coal seam to be mined and the underlying sandstone aquifer comprise the water-bearing strata of the shallow groundwater system in the mine area. The silty and clayey overburden is considered an aquitard.

The underlying sandstone aquifer is comprised of semi-indurated sands and silty sands which are separated from the overlying lignite bed by a clay layer which averages about eight feet thick, thinning to near zero in parts of the permit area. In the northern part of the general area, the aquifer is confined by the underclay of the lignite bed, while farther south along the lignite outcrop the aquifer goes through a transition to an unconfined condition.

The lignite bed occurs as a single seam with an average total thickness of 33 feet and a saturated thickness of about 15 feet, split by clay partings into two or three seams in some portions of the mine area. Recharge to the lignite aquifer is through local infiltration of precipitation. It discharges principally by leakage to the underlying sandstone aquifer, or to a lesser extent by lateral flow to local streams. The degree of hydraulic conductivity for this unit is dependent on the local fracture porosity.

3.2.3 Presentation of Case Study

3.2.3.1 Baseline Data

The applicant's groundwater monitoring facilities include 48 piezometers within and near the mine area. Of these, 31 are in the overburden and 17 are in the lignite seam to be mined. A total of 9 wells are in the path of the advancing pit and will be removed by mining. A number of these wells were installed by the U.S. Geological Survey, which has been studying hydrologic impacts of mining in this area since the early 1970's. Some of the wells were installed by the North Dakota State Water Commission.

The groundwater monitoring program consists of monthly readings of static water levels (SWL) in each piezometer and collection of samples for chemical analysis on a semiannual basis. Analyses are done for all samples specified in North Dakota Rule 69-05.2-08-06.

The SWL data, together with geologic cross sections prepared by the applicant, were used to determine areas where the overburden and lignite aquifers were under confined or unconfined conditions. The SWL data were also used by the applicant to construct potentiometric-surface maps for the coal and overburden.

Results of pump tests conducted by the applicant were provided, indicating a low transmissivity for the underburden sandstone aquifer. No hydraulic data were included in the application for the overburden, lignite, or spoils.

Water-quality data from the applicant's groundwater-monitoring program were provided in the application. A limited analysis of the data was provided to show temporal and spatial variability of the groundwater quality for the lignite and underburden sandstone. Results showed that:

1. Water quality in the lignite is variable, generally dominated by sodium, sulfate and bicarbonate ions, and individual wells showed consistency in dissolved constituents over time. Spatial variation in water quality in the lignite was not discussed.
2. Water quality in the sandstone aquifer below the coal is also dominated by sodium, sulfate and bicarbonate ions. The poorest-quality water is located south of the mining area and south of the lignite crop line, where the underburden sandstone aquifer is near the surface.
3. Water-quality data for five pairs of adjacent lignite and underburden-sandstone wells showed similar water quality for the lignite and sandstone. In general, the sodium and bicarbonate concentrations are lower in the lignite wells than in the adjacent, deeper sandstone wells; sulfate is generally higher in the lignite water. There

was an observed pattern of decreasing sulfate concentrations with depth.

4. Water samples from wells immediately south of the mine were very high in sulfate and TDS concentrations.
5. In general, the water in all wells exceeds both drinking-water and irrigation-water standards (see Table 1).

The application also contained open-file data obtained from the U.S. Geological Survey from X-ray diffraction studies used to determine the mineral composition of the strata between the lignite and the underlying sandstone aquifer.

3.2.3.2 Analytical Techniques

The drawdown impact is based upon an extension of historical data obtained from monitoring wells within the general area of the mine (see Table 6). Coal mining operations began about 1946, while the first monitoring well was installed on January 5, 1977. The potentiometric-surface maps indicate water levels under current conditions. Therefore, the measured impacts to the groundwater system due to mining are from 1977 and not since the beginning of mining. No long-term drawdown estimates were performed for the mine area. No discussion was provided describing how boundary conditions might be encountered that would act to limit or increase the extent of drawdowns around future pits (refer to discussion in Section 2.4.2.1). By this extension of existing data the applicant stated that at a distance of more than one mile from the pits the aquifers would remain under confined conditions.

The postmining potentiometric surface was predicted to return to its premining levels. No computations were presented to support this, and it was stated in the permit application that this prediction was not conclusive as the postmining spoil aquifer characteristics could not be accurately predicted.

The postmining spoil-aquifer water quality was estimated from data obtained at other mines. No analyses were provided to support the use of these other data at this mine, such as documentation of similarities in existing water quality and overburden geochemistry (refer to discussion in Section 2.4.2.4). Because of the poor quality of existing groundwater in the area and the lack of impact to significant regional aquifers, degradation of groundwater quality did not appear to be an issue at this mine. The applicant provided evidence that most of the domestic and livestock wells in the area are completed in units stratigraphically below the lignite and underlying sandstone aquifer, supporting the contention that adverse impacts will be minor.

3.2.3.3 Monitoring and Reporting

The applicant has committed to the continued monitoring of wells throughout mining and reclamation and to the installation of monitor wells in the spoils. The regulatory agency has agreed to allow reduction of the water-level measurement frequency from monthly to quarterly for all wells except those installed in spoils, based on an analysis of the historical water levels. The applicant contends that, in view of the wealth of historical data and lack of proximity to or demonstrated effects on water supply wells, any significant water-level trends in the sandstone and lignite aquifers can be demonstrated using semi-annual monitoring. The frequency of SWL measurements is not specified in North Dakota regulations (see Table 4), and therefore this change in the monitoring schedule is at the discretion of the regulatory authority.

Water levels in newly installed spoils wells will be monitored on a monthly basis until water levels stabilize, and quarterly thereafter. Water quality in the spoils will be monitored semi-annually.

All water-quality analyses will include parameters required by North Dakota regulations (Table 4). Water quality sampling and analyses at the mine are currently handled by the USGS using standard, state-of-the-art sampling and analytical techniques. No change in this arrangement is foreseen for the immediate future. The results of this monitoring program will be reported to the regulatory authority on a semi-annual basis to coincide with the operator's surface-water reporting schedules. Annual water-quality sampling will occur in August or September, with an additional sample taken in March or April for the spoils wells. The semi-annual water-level readings will be taken at these times also.

The applicant states that groundwater monitoring will continue according to this schedule until it is determined through the bond release process that hydrologic monitoring is no longer necessary for the area in question (see Table 5).

3.2.3.4 Evaluation Criteria

The groundwater monitoring program will continue to be used to monitor the effects of mining on the groundwater system and to monitor the quality of water in both the pre- and postmining aquifers. This monitoring will continue until the reclamation performance bond is released, which is contingent on a finding of no significant harm to groundwater resources (refer to Table 5). No numerical standards were provided to use as a goal for groundwater-quality restoration.

3.2.4 Identification of Issues

No calculations were made to quantify the time for reestablishment of groundwater flow in the backfilled spoils. Uncertainty exists as to how long this might take (see Section 2.4.2.3), and groundwater monitoring data collected prior to the time that flow is reestablished in the spoils may not be meaningful. The applicant has committed to monitoring water quality in the spoils. However, no numerical standards have been established to determine whether spoil-water quality is acceptable. Bond-release criteria are keyed to the lack of "significant environmental harm" to water resources (Table 5), but this is not defined in the context of spoil water quality.

In view of the fact that the time required for establishment of groundwater flow in the spoils may be much greater than that allowed for bond-release evaluation, there is a need to develop a method to assess the probability for successful reclamation of the groundwater system.

3.3 Case Study C

3.3.1 Focus

This case study illustrates data and analytical techniques required to restore an important wetland habitat which will be destroyed by mining.

3.3.2 Description of Mine and Hydrologic Setting

This mine is a surface lignite mine which began operations in 1976. The lignite is hauled by truck to a tipple and then delivered by conveyor to a power station located south of the mine. Current production rate at the mine is approximately 5.6 million tons per year.

The permit area is located on the Coteau Slope of the Great Plains physiographic province. The Coteau Slope is characterized by moderate local relief except in the vicinity of major valleys. Drainage is well developed, with stream courses draining southward and westward to the Missouri River.

The region has a typical continental climate with widely ranging temperatures and precipitation. The site receives an average annual precipitation of 16-17 inches. Most of the precipitation occurs in the spring and summer months and is associated with thunderstorm activity which can produce large amounts of rainfall in a short period of time.

The permit area includes approximately 2,090 acres. The watersheds are characterized by gently rolling terrain sloping downward on all sides to a slough complex south of the permit area. The slough complex is composed of two major wetlands along with several smaller wetland areas, and is ultimately drained by a coulee, which is considered an ephemeral stream from the slough complex downstream for several miles. The coulee eventually becomes intermittent as it approaches the Missouri River as a result of spring discharges along its channel. The Missouri River is located approximately nine miles from the proposed site.

Fifteen wetlands exist within the permit area. Of these, 10 will be eliminated in accordance with landowner preferences, 2 will not be affected, and 3 will be restored to approximate premining conditions. In addition, 2 new wetlands will be created on the reclaimed surface.

3.3.3 Presentation of Case Study

3.3.3.1 Baseline Data

Wetlands were identified and classified during the premining land use analysis. The classification was based on both land use and on fish and wildlife values. The classification showed that the wetlands can have significant fish and wildlife values but are generally undesirable as cropland.

Baseline data collected during the identification and classification of the wetlands included:

1. Water quality, including temperature, dissolved oxygen, pH, electrical conductivity, TDS, silica, iron, manganese, calcium, magnesium, sodium, potassium, bicarbonate, carbonate, sulfate, chloride, fluoride, nitrate, boron and hardness of water in wetlands and associated shallow wells,
2. Temporal variations in the water-quality parameters listed above,
3. Vegetation, including species, cover, and production, and
4. Information on geology and soil types.

Some of the data were collected by the applicant and some by the U.S. Geological Survey in a special wetlands investigation by that agency.

In addition to baseline data, the applicant assembled other information on the wetlands for use in the analytical techniques described in the following section. This information is tabulated below:

1. Precipitation, evaporation, transpiration and seepage rates were obtained from published literature.
2. Physical dimensions of wetlands, including area, shape, depth, and water-storage capacity, were determined from topographic maps and surveys.
3. Drainage basin parameters for the watersheds contributing runoff to the wetlands were determined from available topographic maps, soil maps, and observations of vegetation and land uses.

3.3.3.2 Analytical Techniques

The three wetlands to be restored and the two new wetlands that will be created were designed to simulate naturally-occurring wetlands. Design criteria included:

1. An oval shape to simulate natural wetlands,
2. Ratio between drainage area, and hence runoff into the restored wetland, and the water-storage capacity of the wetland to simulate the premining hydrologic balance of natural wetlands, and
3. Relationships between depth, water-surface area and storage capacity of the wetlands in an attempt to restore wildlife habitat and aquatic vegetation communities.

For the wetlands that will not be restored after mining, the permit applicant quantified this loss of water storage and the resulting increase in area streamflow by the use of the TR-20 computer model (refer to Section 2.3.2.1). For input to this model the applicant developed or obtained the following information:

1. Drainage basin parameters, including drainage area, length of the longest watercourse, relief, hydrologic soil types, and land use and vegetation characteristics,
2. The relationships between storage capacity and water-surface elevations for the wetlands to be removed in order to route the computed rainfall-runoff through these wetlands to quantify their role in reducing peak discharges during intense rainfall events by temporarily storing a portion of the resulting runoff,
3. Regional rainfall frequency, duration and intensity relationships from published literature sources,
4. Drainage basin parameters for the postmining basins to quantify peak discharges that will result from various precipitation events without the temporary storage that was provided by the wetlands, and
5. Antecedent moisture conditions in order to estimate the seasonal variation in runoff potential for the various drainage basins.

3.3.3.3 Monitoring and Reporting

The applicant realizes that the construction of these two wetlands is a pioneering effort in mined-land reclamation. As reclamation and wetland-reconstruction proceed, the applicant intends to monitor the process closely. Various regulatory agencies, as well as university and research organizations, will continue to be consulted for advice and direction.

Water quality in the reclaimed wetlands will be monitored during periods of high and low water for parameters measured in undisturbed wetlands. The average values for these parameters will be compared to baseline averages and ranges for the same parameters.

Water levels in reclaimed wetlands will be monitored every two weeks by reading a staff gage graduated in 0.1-foot increments placed in the deepest portion of the wetland. These data will be compared to water levels to be monitored in similar wetlands within the mine area. Fluctuations in water levels will be evaluated using these measurements and precipitation data.

3.3.3.4 Evaluation Criteria

An Office of Surface Mining (OSM) stipulation to the permit stated "....because of limited experience in reclaiming wetlands, the applicant will develop standards for reclamation success for regulatory authority approval prior to reclamation."

Reclamation success, for most land uses, is generally based upon an assessment of vegetative production and cover. When an area meets an "equal-to-or-better-than" production and cover standard, it may be released from bond. Wetlands, however, are important as wildlife habitat and for water retention. Therefore, forage production and cover were not considered to be the most important parameters for evaluation of reclamation success. A wetland may produce a tremendous amount of forage but lack the diversity necessary to satisfy its utility as good wildlife habitat. Cover, which is important for erosion control, is not an important parameter for evaluation of wetlands since wetlands are areas of sediment deposition, not erosion.

In response to the OSM stipulation the applicant proposed the following method for determining reclamation success. It was proposed by the applicant that evaluation criteria be based on an assessment of (1) water quality and quantity, (2) vegetation community patterns indicating levels of diversity, and (3) wildlife-use patterns. Data on these three items will be collected on a regular basis during mining and reclamation. Data will then be reviewed by a Wetlands Advisory Committee. The Advisory Committee will consist of selected personnel from the following four government agencies:

1. North Dakota Game and Fish Department,
2. U.S. Fish and Wildlife Service, Northern Prairie Wildlife Research Center,
3. North Dakota State University, Botany and Zoology Departments, and
4. North Dakota Mining and Mineral Research Institute.

Annually, after the data are collected, and upon the applicant's proposal for bond release for any wetland, the Advisory Committee will review all data collected to date. A field review will also be conducted. The Committee will then recommend action to be taken. The North Dakota Public Service Commission will make a bond-release decision based on the Advisory Committee's recommendations, its own review of collected wetlands data and field conditions, compliance with the wetlands water-quality success standard, and compliance with other applicable laws and regulations regarding reclamation.

3.3.4. Identification of Issues

Rather than have a mining permit denied because of the existence of an important ecological system of unproven reclaimability, the applicant was given the opportunity to develop innovative methods for designing the reclaimed environment and for evaluating the success of the reclamation. The result is the initial development of a technology for the reclamation of wetlands.

It was not stated in the application what measures would be taken in the event that monitoring indicates that the wetlands cannot be restored. Due to disruption of the overburden and placement of soils in the bottoms of the wetlands that differ from those deposited in natural wetlands, the wetlands may not store water due to infiltration and percolation. If this occurs, the wetland will not be restored and the enhanced surface recharge may adversely affect spoil-water quality (refer to Section 2.4.2.4).

3.4 Case Study D

3.4.1 Focus

This case study examines whether the permit process is more efficient when the mine is new. While the time to obtain a mining permit does not appear to have changed dramatically, the State regulatory authority is of the opinion that a well-trained professional reviewing staff has enhanced the quality of the permits (Jim Berg, North Dakota Public Service Commission, March 1985, personal communication). The ground- and surface-water reclamation techniques are also evaluated to determine if there has been an evolution of the reclamation techniques over time. The entire application was prepared under the current regulatory framework, and there are no outstanding hydrologic features in the permit area.

3.4.2 Description of Mine and Hydrologic Setting

This mine is a surface coal mine located in North Dakota. The permit area contains about 1,200 acres. The mine is a single-seam stripping operation, scheduled to ultimately produce 9.9 million tons of lignite annually. The lignite will be conveyed to a nearby power plant and boiler facility.

The mine is on the southeast flank of the Williston Basin, a deep structural basin. The topography of the area can be characterized as moderate relief except in the vicinity of major drainages, where relief can be quite pronounced.

Surface drainage from the permit areas is into an ephemeral stream. The major aquifers are in consolidated rock, undifferentiated lignite aquifers, glacial outwash and alluvial aquifers. The latter group contains the greatest supply of groundwater within the permit area.

3.4.2.1 Baseline Data

Few baseline data were presented in this permit application document. Instead, the applicant provided summaries of data collected by others for nearby areas. These data sources and the types of data utilized from each are listed below.

1. Environmental impact statements prepared for the power plant and the boiler facility to which this mine provides

coal were used to prepare a general description of the hydrology of the mine vicinity.

2. U.S. Geological Survey streamflow data from surface-water stations located in the watershed of an intermittent stream downstream from the mine area were used to prepare a description of streamflow characteristics within the mine area.
3. Data from studies prepared for two nearby mines, together with published reports of the North Dakota Geological Survey, were used to characterize the groundwater of the mine area, both before and after mining.

Data actually collected by the applicant and submitted in the permit-application document included the following.

1. Qualitative descriptions, including channel shape, vegetation, erosional features and flood-plain characteristics, of the two streams to which the ephemeral streams within the mine area are tributary.
2. Results of single-well response (slug) tests conducted on monitor wells in and adjacent to the permit area.

In addition, maps depicting premining and postmining topography, together with soil and vegetation types determined from site-specific studies, were used to prepare input data for the rainfall-runoff estimating technique described in the following section.

3.4.2.2 Analytical Techniques

Calculations of the surface-water quantity impacts of the mining operation were performed by computing premining and postmining peak discharges at a point located downstream from the mine area on the stream that drains most of the land that will be disturbed. The flood-estimating technique used was a handbook prepared by the SCS (USDA, 1979) which contains curves that can be used to determine runoff hydrographs for various precipitation events given selected drainage-basin parameters (refer to discussion of flood-estimating techniques in Section 2.3.2.1). Input data for this method included premining and postmining values for:

1. Runoff curve numbers,
2. Drainage area,
3. Channel length and slope, and
4. Precipitation amount.

No use was made of the aquifer hydraulic characteristics determined from the premining pump tests. The applicant used static water level-data from existing monitor wells to construct potentiometric-surface maps of the aquifers to be disturbed. These maps were used to show general directions of groundwater flow and interactions between aquifers. No predictions of pit inflows or drawdowns were presented.

Studies by others (Moran et al., 1978; Van Voast et al., 1977, 1978; and Groenewold et al., 1979) were used to make general predictions regarding spoil-water quality.

3.4.2.3 Monitoring and Reporting

The applicant has proposed a surface-water monitoring program that consists of:

1. A crest-stage gaging station that is read following each major storm and at least weekly during spring runoff,
2. Three stations consisting of water-level recorders that are operated year-round except during the winter months, and
3. Water samples collected during runoff events from the four stations listed above and analyzed for required parameters (see Table 4).

All the stations listed above are on ephemeral streams.

The groundwater monitoring program consists of:

1. Static water-level measurements in 56 observation wells on a monthly (for wells within one mile of the mine area) or quarterly (for other wells) schedule, and
2. Collection of water samples for quality analysis from all wells once each year, with selected wells to be sampled semiannually or quarterly to detect temporal variation in water quality.

The applicant intends to replace all monitor wells destroyed by mining with new monitor wells completed in the spoils. Other spoil-aquifer monitor wells will be installed at locations yet to be determined. Monthly SWL readings will be taken in spoil wells, and water-quality samples will be collected and analyzed quarterly.

Surface-water and groundwater monitoring data will be submitted to the regulatory authority in quarterly reports. These reports will include data from 12 U.S. Geological Survey surface-water monitoring stations off the mine area but in the general vicinity.

3.4.2.4 Evaluation Criteria

The surface-water monitoring network was designed to collect data adequate to characterize variations in streamflow quantity and quality from both disturbed and undisturbed areas. The application states that data collected prior to and during mining from three watersheds will be analyzed to determine impacts of mining on streamflow quantity and quality. No specific plan was provided to indicate how the surface-water monitoring program would be used to evaluate the success of surface-water restoration.

The groundwater-monitoring program also was designed to assess the effects of mining on the groundwater system. No numerical criteria were presented with which to utilize the data to evaluate the success of groundwater restoration. No predictive techniques were employed to predict groundwater drawdowns, and therefore the monitoring cannot be used to evaluate a predictive technique.

3.4.3 Identification of Issues

This mine was selected for case-study analysis to examine the efficiency of the permitting process for new mines permitted under the current regulatory framework and to assess whether analytical methods have evolved with time.

Almost no information was presented concerning restoration of the surface-water system. If the technology has evolved with time, it is not apparent from information in the application document.

The applicant relies heavily on the use of data developed by others to predict postmining groundwater characteristics. Apparently the data from other areas provided the regulatory authorities with sufficient information to issue the permit.

From the lack of specific information provided in this permit document, one may conclude that the expanding knowledge about hydrologic aspects of coal mining in general is promoting permitting efficiency by reducing the amount of analysis required of new permit applicants.

3.5 Case Study E

3.5.1 Focus

The focus of this case study is an assessment of the sources of data and methods of analyses used by applicant to perform a cumulative hydrologic impact assessment (CHIA) for its proposed mining operation. Because of the thoroughness of the applicant's hydrologic studies, analyses are also provided for the AVF investigation, the mining and reclamation plan, and the probable hydrologic consequences (PHC) assessment.

This case study concerns a proposed mine for which the permit application was submitted to the Montana Department of State Lands (DSL) on December 1, 1981. The applicant has not previously conducted strip coal mining operations at the proposed mine site, nor at any other location in Montana. Subsequent to its submittal, the proposed mine application was revised three times in response to completeness and technical-review deficiency comments put forth by the DSL. Completion of the Technical Environmental Assessment (TEA) by the DSL is not expected until approximately late spring 1985, and the permit application has not yet been approved.

Much of the permit area of the proposed mine lies within and adjacent to the valley of a small perennial stream, and therefore as required by the strip mine rules and regulations of the State of Montana, the applicant completed an alluvial valley floor investigation prior to submittal of the permit application. In review of the report of this investigation the DSL declared that broad areas of the valley floor are classified as an alluvial valley floor significant to farming. Because of this AVF declaration, considerable effort is expended in the mine-permit application in describing the probable effects on essential hydrologic functions from mining adjacent to the valley floor, and on demonstrating that in the postmining environment the quality and quantity of groundwater and surface water in the valley floor will be similar to premining conditions.

During the application review process the Montana Department of State Lands requested that the applicant determine the PHC for the entire life of the mine (30-year mine plan) as well as perform a CHIA of all anticipated mining in the area. The DSL specified that the PHC determination include hydrologic impacts associated with a proposed coal strip mine operation planned by another company immediately adjacent to the applicant's 30-year mine plan area. The area encompassing "all anticipated mining" for the CHI assessment was selected by the applicant and includes ten proposed and active coal strip mine operations in Wyoming and Montana.

3.5.2 Description of Mine and Hydrologic Setting

The proposed mining area is located near the western edge of the Powder River structural basin in southeastern Montana. The topography of the site is relatively rugged, and the maximum topographic relief is about four hundred feet. Due to its location in the continental interior on the lee of the Rocky Mountains, the proposed mining area is semi-arid and is characterized by hot summers and cold winters. Annual precipitation averages approximately 12.4 inches per year. April, May and June are typically the wettest months.

The permit area for the proposed mine's five-year mine plan is 1905 acres. The potential life-of-mine area is much larger, encompassing approximately another four square miles. Maximum proposed production is about eight million tons per year. The surface of the entire area is comprised of the Paleocene age Fort Union Formation overlain by the Eocene age Wasatch Formation. The applicant proposes to mine four coal seams, all of which are contained in the Fort Union Formation. All mining will be by the truck and shovel method. Throughout most of the proposed mine site the upper three seams converge to form one seam 80 to 83 feet thick. The fourth seam is separated from the lowest of the upper three by 65 to 100 feet of interburden. No other active mines in the immediate area (three mines) or proposed mines (two mines) have mined or propose to mine this lowermost coal seam. The regional dip of the coals in the vicinity of the proposed mine is generally 1 to 3 degrees to the east or northeast. Several high-angle faults transect northeast-southwest through the life-of-mine area. Displacement on these faults is as great as 200 feet.

Portions of the proposed mine lie in the drainage basin of a small perennial stream with a drainage area of about 51 square miles. This stream joins a large perennial stream about one-half mile south of the 30-year mine plan area. The large perennial stream originates in the Big Horn Mountains of Wyoming some 30 miles west of the proposed mine site. Flows in the small perennial stream are heavily regulated for flood irrigation from two main ditches; however in the summer flows are normally insufficient for this purpose. Flows in the large perennial stream are heavily regulated by numerous diversions and by a large reservoir which is located about three miles east of the proposed mine site. The applicant's 30-year mine plan area also includes numerous small ephemeral channels which are tributary to one of the two perennial streams in the area.

Both the Tongue River and Wasatch Formations are comprised predominantly of shales, siltstones, claystones, coal and clayey sandstones. Hydrologic studies conducted by the local mining companies as well as the applicant's CHIA indicate that the coal seams are the only aquifers to be affected by mining that are continuous and can be correlated over broad areas. The claystones, siltstones and shales are of low permeability and do not form aquifers. Where present, the sandstone units are lenticular and discontinuous and thereby form only local aquifers. By virtue of their high clay and silt content, yields from the sandstone aquifers are generally very low. Other local aquifers include the saturated alluvium of principal stream valleys and scoria deposits that have formed where strata adjacent to coal seams were baked and fused by the natural burning of the coal seams. Although the quality of groundwater in the coal seams normally does not meet drinking water standards (Table 1), the coals have historically been widely exploited for both domestic and stock-watering uses. The applicant's PHC and CHIA determinations indicate that groundwater in the coal aquifers is confined and regional flow is downdip from recharge sources at outcrop and burned contact zones three to six miles west of the proposed 5-year mine plan area. The coal aquifers discharge at an operating mine and to a reservoir on the large perennial stream approximately three miles east of the applicant's 5-year mine plan area.

3.5.3 Presentation of Case Study

3.5.3.1 Baseline Data

Hydrologic studies conducted by the applicant for preparation of the proposed mining and reclamation plans utilized a large hydrologic and geologic database. In the groundwater regime the data were derived from monthly monitoring of 111 observation wells developed in coal, coal overburden and alluvium of the stream valleys. Many of the wells were independently constructed by the Montana Bureau of Mines and Geology (MBMG) several years prior to the initiation of the applicant's study, and were the subject of published reports by that agency. These reports include: Cole and Sholes, 1980; Hedges et al., 1976; Van Voast, 1974 and Van Voast and Hedges, 1975. Other wells included in the applicant's groundwater database were constructed by another mining company in preparation of their permit application, and a third group were constructed by the applicant. By compiling the various testing and monitoring data of numerous observation wells and by supplementing these data with additional monitoring and testing, the applicant's mine application thoroughly evaluates groundwater flow and quality characteristics for a broad area in all directions from the proposed operation.

In the surface-water regime, the mine application relies upon streamflow and water quality data reported by the USGS from a continuously-recording station on the small perennial stream about 1.5 miles upstream of the permit area, and for the large perennial stream from a station about three miles downstream of the mine-permit area. The applicant further augments these data by reference to unpublished streamflow and water quality information collected by the MBMG, water quality data collected by another mining company, and streamflow and water quality data collected by the applicant during the course of the baseline hydrologic studies. The applicant also installed a weir with continuous recorder to monitor flow in a small ephemeral tributary that will be disturbed by mining. To provide useful information for designing restored channels, the applicant surveyed and/or measured from topographic maps longitudinal profiles and cross sections for each of the ephemeral tributaries that will be disturbed by mining. Particle size analyses were performed on channel bed and bank samples collected at each surveyed cross section location to help assess the premining erosional state of the streams. Other stream-channel and drainage-basin characteristics commonly described in mine-permit applications such as stream orders, relief and bifurcation ratios, drainage densities and channel meander characteristics are not included in the mine-permit application.

The applicant's AVF investigation was site-specific to the valley floor adjacent to the proposed operation and includes approximately a four-mile reach of the stream. The objective of the study was to determine the existence of an AVF as defined by State and Federal mining regulations, and to determine the extent, if any, of land significant to farming. As previously stated, the AVF study was submitted to the DSL prior to submittal of the mine-permit application.

Groundwater data utilized in this study were from the monthly water-level monitoring and selected water-quality sampling of 63 observation wells developed in the valley-fill sediments. The wells were constructed by the applicant, the MBMG and another mining company over a period of approximately four years. The applicant also constructed 17 backhoe pits and 14 neutron-probe access tubes to further assess the extent of subirrigation and the effects of shallow groundwater conditions on vegetal productivity. Using the lithologic logs of the observation wells and of coal exploration holes drilled in the area, six geologic cross sections were drawn illustrating the thickness, lithologic character and saturated zone of the valley floor materials. The quality and quantity of streamflow in the stream were evaluated using three years of data reported by the USGS from that agency's continuously-recording gaging station upstream of the proposed mine operation. Peak flows in ephemeral tributaries were estimated for various storm duration and recurrence intervals using regional flood studies (see Section 2.3.2.1) to evaluate water availability for potentially irrigable acreage at the mouths of these small valleys. Utilizing reported data, the quality and quantity of flows in the small perennial stream were evaluated in terms of suitability for flood irrigation and the results compared to present and historical irrigation practices.

In the groundwater regime, the applicant's AVF and permit-application studies utilize up to about 17 months of groundwater-level monitoring. The applicant conducted aquifer hydraulic tests at 28 wells and, in addition, provided the unpublished results of 16 well tests conducted by the MBMG. Eight monitoring wells were sampled by the applicant as many as two times each. In the surface-water regime, most flow and water-quality data were taken from published reports of the USGS and MBMG, although the applicant also collected four streamflow samples and a sample of a groundwater seep in the valley floor.

The applicant's PHC evaluation includes analysis of hydrologic impacts associated with another proposed mine that will be adjacent to the applicant's proposed mine in the same stream valley. By special stipulation of the DSL, that portion of the PHC evaluation concerning impacts to coal seam aquifers also included an existing mine located in Wyoming approximately 1.5 miles west of the west boundary of the applicant's 30-year mine plan area. This existing mine has only one small pit, which has been open but inactive since about 1977. No new data are presented in the PHC determination that do not already exist in the applicant's mine-permit application other than coal aquifer potentiometric elevation and hydraulic data taken from the permit application of the one existing mine.

Ten proposed or active coal strip mines are included in the applicant's CHI assessment. These mine areas lie essentially in all directions from the applicant's proposed mine, are up to five miles distant from the applicant's 30-year mine plan area, and are located in the valley of the large perennial stream or near the mouths of small streams tributary to the perennial stream. In the groundwater regime the CHI assessment considers only the three uppermost coal seams that will be mined at the applicant's mine, since regional aquifers are not found in the coal overburden and interburden materials. The assessment erroneously states that no mines other than the applicant's proposed mine have mined or propose to mine the fourth lowest coal seam. In fact, this seam has been mined for at least several decades at one other mine in Wyoming--the mine furthest to the southeast from the applicant's proposed mine in the CHI assessment. The applicant's permit application indicates that this lower coal subcrops in the valley of the large perennial stream downstream of the aforementioned operating mine. Accordingly, impacts to this coal aquifer from operations at the mine in Wyoming should not be cumulative with impacts from mining at the applicant's proposed mine, and the error in the CHI assessment is inconsequential.

Prior to the applicant's effort, there apparently was no published information correlating regional coal-seam hydrogeology through the entire area included within the applicant's CHIA. For this reason, the assessment first presents a map illustrating the subcrops, outcrops, burn lines, fault traces and convergence and divergence zones of the various coal seams, as well as the potentiometric configuration and direction of groundwater movement in the coals. This information was compiled from hydrogeologic and coal-resource evaluation reports of the Montana Bureau of Mines and Geology (Cole and Sholes, 1980; Hedges et al., 1980; Matson and Blumer, 1973; Thompson and Van Voast, 1981; Van Voast and Hedges, 1975) and of the U.S. Geological Survey (Kanizay, 1978; Law and Grazis, 1972; Law et al., 1979), from data contained within the various mine-permit applications, and from unpublished studies conducted by a mining company already operating several mines in the area. The applicant analyzes the regional groundwater flow patterns and aquifer recharge and discharge sources to determine the mine areas that will be subject to cumulative impacts to water quality and quantity. Predictions of postmining groundwater quality in reclaimed mine spoils of the CHIA area are made primarily by reference to predictions made by the MBMG in a study of the effects of spoil-water quality on the quality of water in the large perennial stream (Van Voast and Thompson, 1982). This study was published while the applicant's CHIA was in preparation and is described in Section 2.3.2.3.1.

The determination of impacts to surface water in the applicant's CHIA focuses on determining potential increases in dissolved chemical constituents and sediment in the large perennial stream. The spatial and temporal variations in potential solute increases in the streamflow are predicted based upon data and conclusions regarding the quality and quantity of groundwater flow in spoils reported by the MBMG (Van Voast and Thompson, 1982). The MBMG study included eight of the ten proposed or active mines considered in the applicant's CHIA. Mining in the CHIA area will disturb eleven principal drainages tributary to the large perennial stream. Potential increases in sediment yield to the river from these drainages are estimated in two ways utilizing two different sources of data. In one method the published sediment yield of a stream draining an unreclaimed coal strip mine located near the CHI assessment area (Ringer et al., 1979) is used as a worst-case example. The second method, which is perhaps more realistic, utilizes a sediment-accumulation rate reported by Dendy and Champion (1973) for a reservoir on the large perennial stream. Apparently, no information is available from any of the four active mines in the applicant's CHI assessment area to quantify sediment yields from reclaimed mine spoils.

3.5.3.2 Analytical Techniques

Numerous analytical techniques were employed by the applicant in the hydrologic studies conducted for the proposed mine. Although few of the techniques may be considered unique or state-of-the-art in hydrologic modeling, the analyses thoroughly evaluate premining hydrologic conditions, provide for protection of hydrologic resources during mining, and plan for restoration of groundwater and surface-water systems after mining. In this section, the analytical techniques presented in the applicant's AVF investigation and in the applicant's mine-permit application document are briefly reviewed. A thorough discussion of the analytical techniques found in the PHC and CHIA is also provided.

Analyses of hydrologic data in the AVF investigation are relatively simplistic and are primarily oriented to the inventory and documentation of the geologic characteristics of alluvium, occurrence and quality of water in alluvium, and the quantity, quality and use of streamflow. Apparently, the objective in the AVF report was not to quantify all variables of the hydrologic balance of the valley floor but to provide the basic information necessary for the DSL to determine the boundaries of the AVF as defined by appropriate rules and regulations. In the groundwater regime, the documentation included construction of a surficial geologic map and six geologic cross sections of the alluvium, presentation of water-table maps and an isopach map of alluvial thickness, soil-moisture versus depth profiles from calibrated neutron-probe measurements, and descriptive logs of plant-rooting depths and moisture levels observed in soil-test pits. Water quality analyses and aquifer pumping test results are provided for selected alluvial wells.

The documentation of surface-water resources includes presentation of published streamflow and water quality data, determination of the seasonal availability and use of streamflow for flood irrigation, and mapping of the extent of flood-irrigated and subirrigated land. Only a few years of streamflow records were available for the small perennial stream in the applicant's permit area, and the long-term average streamflow available for agricultural use as well as total average annual runoff are estimated by comparing the available runoff data with long-term precipitation records.

The applicant's permit application thoroughly analyzes the hydrologic functions of the valley floor as well as regional groundwater and surface-water flow rates and the geomorphic characteristics of the stream valleys. In the regional groundwater assessment, rates and directions of flow in aquifers are quantified through flow-net techniques using potentiometric surface maps for the confined coal aquifers and water-table maps for the alluvial aquifer of the small perennial stream. The analysis of groundwater conditions in coal includes an area much larger than the proposed five-year mine plan permit area, and illustrates coal-aquifer recharge areas several miles west of the proposed mine and coal discharge areas several miles east of the proposed mine. The flow-net techniques are used to identify EHFs such as aquifer recharge and discharge sources, intercommunication between aquifers, and the effects of geologic structure on groundwater movement. Point measurements of flow were made in numerous sites on the small perennial stream at about the same time that groundwater levels in alluvial wells were measured. In this manner, the applicant identifies gaining and losing reaches of the stream and determines the total volume of combined surface- and alluvial groundwater flow through the valley system. Groundwater quality data from samples taken upgradient and downgradient from the proposed mine area are used to illustrate the natural chemical evolutions along groundwater-flow paths in coal and alluvium, and changes in water quality resultant from local activities such as irrigation in the lower portion of the small perennial stream valley.

The applicant's mine-permit application assesses premining streamflow and erosional conditions using predictive techniques and data from field monitoring. Peak flows in the small perennial stream and in ephemeral tributaries are estimated by the Johnson-Omang (1976) method for floods of various recurrence intervals. Longitudinal profiles and cross sections of stream channels were drawn for all streams to be affected by mining. Peak flows from storm runoff events were estimated for each channel cross section using the SCS triangular hydrograph method (1972). In addition, the bankfull capacities of existing channels were computed at each channel cross section using the Manning equation in the slope-area technique. The erosional state of the stream channels is generally described by reference to the channel profiles and cross sections and from visual observations made from field inspections. Sediment-yield rates for the small perennial stream are estimated by a flow duration-sediment rating curve method using data reported for the USGS gaging station on the stream. Sediment-yield rates for ephemeral tributaries of the small perennial stream in the mine area are estimated using a multiple regression technique devised by Cary (undated) from work done in northeastern Wyoming. Sediment delivery ratios for the small perennial stream and ephemeral tributaries are estimated by a standard technique reported by Vanoni (1975).

The applicant's mining and reclamation plans provide many analyses assessing probable hydrologic impacts and techniques for preserving and restoring surface waters and groundwaters. Pit inflow rates from each coal-seam aquifer are predicted for each year of mining through a complex analytical technique that was manually performed (as opposed to the use of a digital computer model). This technique follows an interactive process wherein incremental aquifer drawdowns are calculated through solution of the Theis nonequilibrium equation by locating imaginary pumping wells around proposed pit boundaries. Incremental drawdown values in the vicinity of each pit from the pumping wells are used to estimate potentiometric gradients toward pits which allows estimation of induced inflow rates through solution of the Darcy equation. Aquifer storage releases over the incremental time periods are quantified through solution of the constant drawdown, variable discharge drain equation (after Ferris et al., 1962). One mine pit will intercept a small area of alluvium in the small perennial stream valley in the fourth year of mining. Inflow rates from alluvium to this excavation were estimated with the Darcy equation, and potential drawdowns in alluvium were computed through solution of the constant discharge, variable drawdown drain equation (after Ferris et al., 1962).

The permeability of the proposed mine spoils is predicted to fall within the range reported by various authors (Van Voast, 1974; Van Voast and Hedges, 1975; Rahn, 1976; MBMG, unpublished) for spoils at other mines in northeastern Wyoming and southeastern Montana. Based upon the differences in texture between the materials of the overburden and interburden, and the sequence in which these materials will be hauled back into the pits, the permeability of proposed mine spoils are expected to vary with depth. The primary component of spoil recharge is expected to be horizontal flow from unmined coal seam aquifers. No estimate is given of the time required for the mine spoils to saturate.

The applicant uses a predictive technique developed by Van Voast et al. (1978) to estimate the postmining quality of groundwater in the mine spoils (see Section 2.4.2.4). In addition, the applicant developed a method for predicting the electrical conductivity and sodium concentration of spoil groundwaters, based in part upon overburden paste extract data from a nearby operating mine.

The proposed mine-permit application provides for protection of surface-water resources during mining with plans for a complex system of sediment and pit pumpage ponds and diversion and sediment ditches. Streamflow peak-runoff rates and flow volumes for design purposes were computed using the SCS triangular hydrograph method (1972). Required sediment storage values in settling ponds were calculated using the Universal Soil Loss Equation, or by utilizing the constant storage requirement of 0.1 acre-feet per acre of disturbed land set forth in the State mining rules and regulations.

The effects of pit pumpage water on the quality of water in the small perennial stream and the erosional state of the stream when flows are augmented by pit pumpage are assessed in the proposed mine-permit application. The quality of water in each aquifer is mass-weighted against the computed pit-inflow rate from each aquifer for each year of mining and the results mass-weighted against the low-flow chemical quality of the small perennial stream at various monitoring points. In addition, projected pit-discharge waters are mass-weighted against the quality of low flow in the large perennial stream downstream from mining. The maximum projected pit-pumpage rate is compared to the normal range of flow in the small perennial stream and to the computed bankfull capacity of the channel at numerous points to approximately assess the potential for increased channel erosion from increased flows.

Unique sediment-control and drainage-restoration concerns are associated with the applicant's proposal to create a large overburden stockpile across the mouth of an ephemeral tributary to the small perennial stream. This tributary has a drainage area of about 6.5 square miles and is the largest stream that will be directly affected by mining. The size and position of the stockpile are required by constraints associated with the location and depth of mining. By directive of the DSL, the applicant conducted an AVF investigation of the ephemeral stream and the stream was declared a non-AVF. The stockpile will be constructed in benches, and a ditch will be constructed along the crest to collect runoff from the top area and discharge it over the outslope in a stabilized channel. Where the stockpile covers the ephemeral stream it will be stabilized with topsoil, seeded, and provided with small sediment traps and straw dikes. During mining, flows in the ephemeral stream will be conveyed beneath the stockpile in a culvert.

Because the spoil stockpile lies near the mouth of the sizeable ephemeral stream drainage, strict compliance with mining rules and regulations during reclamation of the area would require a sedimentation pond capable of containing the 10-year, 24-hour runoff event from the entire drainage basin unless the culvert originally beneath the pile is allowed to remain in place. Such a sedimentation pond would inundate much of the reclaimed area in the valley floor. For this reason the applicant proposes to reclaim the channel and flood plain adjacent to the culvert but leave the culvert in place until final bond release. Upon final bond release the culvert will be removed and the remaining channel and flood plain immediately reclaimed. Energy dissipators, such as straw dikes, will be used to prevent channel erosion prior to reestablishment of vegetation in the final reclaimed area.

In addition to the aforementioned ephemeral stream, five ephemeral drainages will be reconstructed in the proposed mine area. The reconstruction designs are based upon recreating the basic premining geomorphic characteristics of the drainages and providing stable, vegetated channels capable of transmitting calculated peak flows. Postmining drainage densities will be approximately equivalent to premining conditions, and all reconstructed channels will have smooth, unbroken profiles that grade evenly into undisturbed reaches above and below reclaimed areas. Most reconstructed channels will be of a compound design, with a large trapezoidal channel to pass the 100-year runoff flows, and a smaller V-notch channel capable of conveying either the calculated 2-year flood flows or the same flow rate as the present channel capacity.

Analytical techniques presented in the PHC and CHIA are described together herein since many of the analyses are identical and are for overlapping geographic areas.

A large portion of the PHC and CHIA is devoted to the regional geologic correlation of coal seam aquifers, identification of regional coal-aquifer recharge and discharge sources and geologic structures controlling groundwater movement, and quantification of cumulative aquifer drawdowns from mine dewatering. In addition, the PHC assessment evaluates potential drawdowns in alluvium of the small perennial stream, potential depletion of streamflow in the stream from alluvial drawdowns, and impacts to the quality of water in both the small and large perennial streams associated with the combined mining activities of the applicant and another mining company in the same area.

The potential for cumulative drawdowns in alluvium of the small perennial stream is assessed simply by determining whether or not the "cones" of depression in alluvium shown on maps by each coal company for their respective mining years will overlap by virtue of their locations adjacent to mine pits or by the phenomenon of groundwater drift. As in all the PHC and CHIA evaluations, the assumption was made that both mines would be in operation simultaneously. The groundwater drift rate in the alluvium of the valley floor is estimated using an average value for alluvial permeability and a maximum observed water-table gradient. Maximum potential streamflow depletion rates associated with drawdowns in the alluvium are computed through solution of a standard one-dimensional groundwater flow equation presented by McWhorter and Sunada (1977). As used, the equation yields conservatively high results.

Potential impacts to the quality of water in both the small and large perennial streams from mine-pit discharges from the two proposed mining activities are evaluated in the PHC assessment utilizing mass-balance calculations for six separate scenarios. Three of these scenarios use streamflow/water quality data from the USGS station on the small perennial stream above the mining areas for low, average and high flow conditions, and three use streamflow/water quality data from a gaging station operated by the other mining company near the mouth of the stream. All of the scenarios also include water-quality and flow data from the large perennial stream. In all examples, the quality and quantity of streamflow under the various flow conditions is mass-balanced with the expected quality and quantity of discharge waters from both mines to determine potential percentage increases of various chemical constituents in both streams.

The two mines that will operate in the drainage of the small perennial stream will disrupt runoff in ephemeral tributaries to the stream as well as to the large perennial stream that is also adjacent to the mine areas. Some of the streamflow intercepted by the mines will therefore be temporarily lost during mining. This potential loss of recharge to the two streams is evaluated under the very conservative assumption that all flow intercepted by the mines is totally lost, with no outflow from the mines to the streams. Under this assumption each ephemeral streamflow loss is quantified by comparison of the computed 2-year flood flow volume above disturbance areas to the 2-year flood flow volume for the entire ephemeral drainage basin. Flood flows are quantified by the Craig and Rankl method (1978). The differences between above- and below-mining flood volumes for each ephemeral stream basin are the estimated annual volume of runoff lost to the main streams.

As directed by the DSL, the applicant's assessment of cumulative coal aquifer drawdowns in the PHC study includes the applicant's proposed mine as well as another mine proposed for approximately the same area and a currently inactive mine located in Wyoming. The assessment includes analysis of the upper three seams at the applicant's mine, which will be mined at all three mine locations, and analysis of the lowest seam to be mined at the applicant's mine, which will only be extracted at that location. Under this scenario, "cumulative" potential drawdowns in the upper three seams from activities at all three mines is estimated by determining the drawdowns associated with each mine block alone and then summing the results. Drawdowns from each mine alone are computed in consideration of the proposed mining sequences, pit configurations and pit distances from aquifer recharge and fault-barrier boundaries, and aquifer hydraulic parameters using a combination of three one-dimensional flow equations for confined and unconfined aquifer flow, or both, to excavations (after Departments of Army, Navy and Air Force, 1971), and by using the constant drawdown variable drain equation (after Ferris et al., 1962). These equations were manually solved in an iterative manner for the various pit locations and planned progression rates. The relative effect of the aquifer drawdowns on streamflow where the coals are in hydraulic communication with streams is discussed.

Life-of-mine drawdowns in the lowest coal seam, which for the mines of the PHC assessment will only be extracted at the applicant's mine, is estimated through solution of the Theis nonequilibrium equation by dividing the 30-year mine plan area into two areas and representing each as hypothetical discharging wells.

Based upon the aquifer-drawdown analysis in the PHC assessment and the locations of regional groundwater recharge and barrier boundaries it was determined that four mines are in the coal groundwater flow system of the applicant's mine, and drawdowns from these mines in the upper three coal seams constitute the "all anticipated mining" cumulative groundwater impact scenario. For this analysis, each mine is simulated as a large-diameter discharging well, and drawdowns as a function of time and distance is computed through solution of the Theis nonequilibrium equation using a BASIC-language computer program. This same basic technique was applied by another applicant for another proposed mine in the area after it was shown that the computed results agreed well with drawdown values that have been observed in the vicinity of an operating pit. The CHIA evaluates the potential impacts to private wells located within the cumulative coal drawdown area. In addition, the potential effects from mine blasting shock waves on local water-well production is discussed.

The temporal and spatial variation in regional postmining groundwater quality is approximated by reference to conclusions set forth by Van Voast and Thompson (1982). These conclusions are described in Section 2.4.2.4.

Potential salt loading to the large perennial stream that drains the areas of all ten mines in the CHI assessment is evaluated by the applicant through modification of procedures followed by Woods (1981) and Van Voast and Thompson (1982) in other mine impact studies (see Section 2.4.2.4). The temporal variation in salt loading is estimated for each mine in each hydrologic flow group by computation of the approximate time for groundwater to move from each mining area to the main perennial stream.

Conservatively high estimates of increased sediment yield to the main perennial stream draining the ten mine areas of the CHIA are computed by two methods assuming that all mines will operate simultaneously and that no reclamation will have been started or completed on any drainages tributary to the main stream at any mine site. One method follows the approach developed by PSIAC (1968) in which a numerical rating technique is applied to each drainage to determine probable sediment yield. In the other method, the sediment yield measured by Ringer (1979) from an unreclaimed mine site in northeastern Wyoming is applied to the total area of all potentially affected drainages. The total sediment yield determined by this latter method is compared to the total annual sediment yield reported for the main stream at a large reservoir on the stream to estimate the potential net increase in sediment yield in the river from all mining.

3.5.3.3 Monitoring and Reporting

No monitoring plans are presented in applicant's CHIA assessment, although a thorough description of the hydrologic monitoring proposed during and after mining is contained in the mine-permit application.

In the surface-water regime the applicant's mining and postmining monitoring proposals include the continuous measurement of streamflow in the small perennial stream upstream and downstream of all mine-related discharge points. Flow will also be continuously monitored in an irrigation ditch that is supplied by the stream within the mine-permit area. Weirs or flumes with continuous recorders will be established below all mine settling ponds for which discharge permits have been obtained, and in consultation with the DSL some of these installations will be retained until final bond release. In addition, flow will also be monitored until final bond release in two of the largest ephemeral tributaries that will be disturbed by mining. Water-quality samples will be taken quarterly at the upper and lower gaging sites on the small perennial stream that traverses through the permit area and analyzed for the required constituents (Table 4). Permitted mine-discharge points will be sampled at frequencies and for parameters specified by the agency regulating mine discharge permits--the Montana Water Quality Bureau.

The applicant's groundwater monitoring plans are designed to detect changes in the quantity and quality of groundwaters throughout the mine plan and adjacent areas. In general, water wells selected for monitoring lie upgradient and downgradient of the proposed mine operation. The plans include 22 alluvial wells; water levels in 20 will be measured monthly, and in the other two alluvial wells water levels will be monitored continuously with recorders. Four alluvial wells will be sampled semi-annually, and the samples analyzed for the complete suite of chemical constituents shown in Table 4. Six other alluvial wells will be sampled quarterly, and the water analyzed in the field for conductivity, pH and temperature. Monitoring plans for the four coal aquifers that will be mined include 27 wells. Water levels in 25 coal wells will be measured quarterly, and, in the remaining two coal wells, will be measured continuously with recorders. Water samples for complete chemical analyses will be collected from four coal wells on a semi-annual frequency. Nine other coal wells will also be sampled semi-annually, and the water analyzed for the field parameters described above. The applicant has further committed to the construction of spoil-aquifer monitoring wells after year 5 of the mine plan, in consultation with the DSL. The number and locations of the spoil wells are not specified.

The reporting of the mine-life hydrologic monitoring data will be to the DSL. Streamflow quantity and quality data will be submitted quarterly, except possibly for the upper gaging station on the small perennial stream. This site is operated by the USGS, and the data will be submitted as they become available. The applicant has committed to the replacement of this upper gaging site if it is abandoned by the USGS. Groundwater monitoring data will be submitted to the DSL in the annual mining reports, or at more frequent intervals if specified by that agency. The applicant proposes that groundwater monitoring continue until, in consultation with the DSL, the success of reclamation is reasonably assured and postmining land uses are equivalent to premining conditions.

Although the proposed hydrologic monitoring plans are expected to be adequate to assess hydrologic conditions during mining, it is noted that no commitment is made to actually perform these assessment analyses. Obviously, as the data become available they could be used to further assess and revise previous conclusions regarding the probable maximum extent and severity of future impacts of the mine alone, as well as cumulative hydrologic impacts from all anticipated mining. It is presumed that these assessments will ultimately be made by the applicant when applying for a new 5-year mine-permit application.

3.5.3.4 Evaluation Criteria

The criteria for evaluating the protection of hydrologic resources during mining and for the restoration of these resources after mining are implicit in the mining rules and regulations which directed the planning and commitments set forth in the applicant's mine-permit application. As discussed in the following section, hydrologic monitoring proposed by the applicant during mining should be adequate to assess protection during mining of groundwaters and surface waters in the vicinity of the mine. On the other hand, it is not entirely certain that monitoring in the period after site reclamation is complete and until final bond release (approximately 10 years) will be adequate to determine the apparent success of surface-water restoration. Moreover, it is highly improbable that the postmining monitoring will be instructive in determining either the final groundwater quality or hydraulic characteristics of the reclaimed mine spoil areas.

Most of the drainages that will be reclaimed at the applicant's mine site will be constructed to pass peak flows of the 100-year runoff event. Guide channels capable of transmitting the 2-year flood event, or of a capacity equivalent to the bankfull capacity of premining channels, will be constructed within most of the 100-year flood-flow channels. It is likely that 2-year flood events will occur at least several times during the postmining monitoring period and that the erosional stability of the guide channels can be readily assessed. Conversely, there is statistically only about a 10 percent chance that a 100-year runoff event might occur during the postmining monitoring period, and therefore little expectation that the erosional stability of the flood-flow channels will be assessed by the applicant.

The repetitious testing of wells in mine spoils in Campbell County, Wyoming has shown that spoil permeabilities tend to decrease with time (Stowe, 1985) as the spoils begin to saturate from groundwater invasion. It is hypothesized that the groundwater invasion may enhance the settling of the spoils. Although no estimate has been made of the time required for the applicant's mine spoils to attain equilibrium with the regional groundwater systems, it is entirely possible that it may be many decades. Since spoil settling will obviously affect the hydraulic and erosional stability of reconstructed channels, especially where the channels join undisturbed stream reaches, it may be many decades after mining before the long-term stability of reconstructed drainages may be entirely known.

The potentially long period over which mining will occur within the regional groundwater flow systems of the proposed mine, combined with small groundwater gradients and the low permeability of the coal and spoil materials, will all act to prolong the time required for the spoils to attain hydraulic and chemical equilibrium within the aquifer systems to perhaps hundreds of years. Similarly, the CHIA estimates that it may be as much as 500 years before leachate from some mine-spoil areas reaches the main perennial stream draining the regional area. From these conclusions it is apparent that the proposed postmining monitoring efforts will in themselves be of marginal use in determining the long-term effects of mining on groundwaters in restored aquifers or receiving streams on either a regional or site-specific basis. This is not to say that postmining groundwater monitoring should not be conducted; some data valuable for the refinement and calibration of existing predictive impact models may be obtained in the postmining monitoring period even if the spoils experience only limited saturation in small areas.

The hydrologic studies conducted by the applicant for the proposed mine, particularly the PHC and CHIA, are particularly thorough and provide the first comprehensive analysis of the regional groundwater systems that will be affected by the various mines in the area. It is likely that these studies will satisfy the mining rules and regulations of the Montana Department of State Lands, and perhaps may be useful to that agency in evaluating the success of hydrologic protection and restoration at not only the applicant's mine but also other mines in the area.

3.5.4 Identification of Issues

This case study points out that even with extensive use of data and with competent technical analyses there remain uncertainties concerning the probable hydrologic consequences and cumulative hydrologic impacts of mining. These uncertainties are listed below.

1. The time required for reestablishment of groundwater flow after mining and reclamation are complete is unknown.
2. The potentially additive effects on solute concentrations in groundwater as it migrates through one mine's spoil area to the next is difficult to predict with current technology.
3. Temporal variations in spoil-water quality with time until steady-state is reached are difficult to predict, and there are associated uncertainties regarding when any evaluation criteria should or could be applied.

Although extensive analyses are presented in the permit-application document and extensive monitoring is proposed throughout mining and reclamation operation, no plan is included to continue to evaluate and if necessary refine the techniques used to predict probable hydrologic consequences and cumulative hydrologic impacts.

The extensive data-collection and analyses presented in this application contrast with the previous case studies, particularly in the design of restored surface-drainage systems and prediction of groundwater impacts. Possible reasons for this are:

1. variations in state guidelines and regulations, and
2. location of the mine with respect to important hydrologic features, including AVFs significant to farming and a major, perennial stream with important fisheries and agricultural values.

3.6 Case Study F

3.6.1 Focus

This case study focuses on a surface coal mine in Montana which has been the site of a considerable amount of research into several environmental aspects of mining, including hydrologic impacts. Information developed at and near this mine has been published and is widely referenced in several permit-application documents in Montana and other states. This case study examines the database and analytical techniques that resulted from the research at this mine, with primary emphasis on groundwater impacts and spoil-aquifer characteristics. This case study corresponds with Case Study C in the Soils and Overburden report (Walsh, 1985).

3.6.2 Description of the Mine and Hydrologic Setting

This mine has been operating in southeastern Montana since 1969, and has a total permitted area of about 2,360 acres. Subsequent to its initial approval, the mine- permit application was revised to update the operation in compliance with the State of Montana's Permanent Program Strip and Underground Mine Reclamation Rules and Regulations. The revised application has been further amended three times to include small additional mining areas. The latest revision was submitted in July 1983 and was approved and the Technical Environmental Assessment completed by the Montana Department of State Lands (DSL) in September 1983.

In the period from 1969 to 1973, some 200 to 250 acres of land were mined and backfilled, but not graded and reclaimed. In compliance with the Montana Strip Mining and Reclamation Act of 1973, the applicant submitted a mine and reclamation permit application. To provide information for the permit application the mining company retained the Montana Bureau of Mines and Geology (MBMG) and the Agricultural Experiment Station of Montana State University to conduct mine-site hydrologic studies beginning in about 1973. At about this same time, the MBMG was also retained by another coal company located about 1.5 miles from the mine under review, and the MBMG study was therefore expanded to a regional investigation of hydrologic conditions within and in the regional vicinity of the two mining areas. The results of the regional study were published by the MBMG (Van Voast et al., 1977). In preparation of its mine-permit application, the mining company of this case study derived essentially all of its descriptions of regional groundwater and surface-water hydrology, mine spoil hydrologic characteristics and potential mine-related hydrologic impacts from the aforementioned MBMG report. By incorporating pertinent information from the large adjacent mining area, the applicant provides a more comprehensive analysis of the relationship of mine spoils to hydrologic systems than would likely have been possible through investigation of the mine area alone.

The hydrologic studies conducted for the applicant by Montana State University (MSU) were essentially site-specific to the applicant's mining area and include evaluation of the long-term viability of a proposed permanent impoundment, determination of potential impacts from mining on a subirrigated field near the mining area, and quantification of changes in the quality of water infiltrating soils in reclaimed areas. The results of these studies have also subsequently been published (Dollhopf et al., 1977; 1979). The information concerning spoil-water quality has been widely referenced and used to predict spoil-water quality in other areas (refer to Section 2.4.2.4) and is described in the following section.

The mine-permit area lies in southeastern Montana near the northwestern edge of the Powder River Basin. The climate of the site is semiarid, with an average annual precipitation of about 16 inches. Most of the land surface consists of flat-topped hills gently sloping towards stream valleys. Some of the drainage divides, however, are steep, with resistant sandstone cliffs approximately 100 feet high.

Nearly all of the mine-permit area is drained by two small, ephemeral tributaries. One of these stream valleys has already been mined through. The two streams join about one mile downstream of the permit area, forming a stream that is in turn tributary to a larger ephemeral or intermittent stream about three miles downstream of the permit area. Mining will eventually disturb about 14 percent of the total drainage area of both streams. The DSL has declared that no AVF exists within or in the vicinity of the mine-permit area. Two stock ponds which existed on the site prior to mining and another impoundment constructed for mine sediment control will be retained for postmining land use.

Two coal seams, both in the Tongue River Member of the Fort Union Formation, are and have been the object of mining at the site under review. Mine production is anticipated to be about 4 million tons of coal per year. The upper seam averages about 25 to 30 feet thick, and the lower seam about 6 to 10 feet thick. Mining of the lower seam has been conducted only where the seam lies within 100 feet or less of the land surface. The thickness of interburden between the seams ranges from about 6 to 35 feet. Overburden and interburden materials are removed and cast into previously-mined pits by dragline.

The coal and overburden within the mine and adjacent areas dip very gently eastward off the flank of a gentle anticline lying about two miles west of the mine. The upper coal seam crops out at numerous locations within the mine-permit area.

Five aquifers occur within the stratigraphic section that has been or will be disturbed by mining. These include the alluvium of the stream channels, sandstones in the overburden, the two coal seams and a sandstone that underlies a shale beneath the lower coal seam. All have historically been used to supply shallow wells for stock and rural-domestic purposes in the regional area. Within the mine area, the alluvium of the stream channels is relatively thin and probably of low permeability. The thickness and lithologic character of the coal overburden varies considerably within the mine area. The percentage of sandstone in overburden was great in the portion of the mine where pits transected the ephemeral stream valley, and the inflow rate of groundwater to the mine from the sandstone was reportedly large. Throughout the mine-permit area and regional area as a whole, the sandstone units are discontinuous and are not considered regionally significant aquifers. Water levels in overburden in the vicinity of the active mine area have not changed greatly, probably because of the discontinuous nature of the aquifers in this strata. Although the yields of wells in the coal seams are generally low, these aquifers are important by virtue of their broad regional extent. Monitoring has shown that water levels in the coals have declined by various amounts depending upon distances and directions from mining operations. In some cases, the coal-water levels have partially recovered as the mine pits were locally backfilled.

Potentially the most significant shallow aquifer at the mine site is the sandstone lying beneath the lower coal seam. Two wells were developed in this aquifer to provide water for the mine office and tipple facilities, respectively. The quality of the water at the office well is reportedly suitable for domestic use (see Table 1). Water quality in this sub-coal sandstone is highly variable (Van Voast et al, 1977). At some wells, the water would be classified as fair for domestic use, and at others it is only fair even for livestock consumption. Water levels in three wells in the sub-coal aquifer in the vicinity of the mine of this case study substantially increased throughout most of 1976, leading to the conclusion that mining has apparently not affected this aquifer.

The quality of groundwater within the various aquifers of the regional area is highly diverse. There is no specific trend of groundwater mineralization with stratigraphic positions of aquifers, position in the flow system, or areal distribution. Furthermore, no specific cation is predominant in water from any particular aquifer. The predominant anion in most groundwaters is sulfate.

Spoils in the permit area of the mine under review which were replaced some 15 years ago are beginning to resaturate to the approximate groundwater elevations that existed prior to mining. Presumably, some of the spoils at the nearby mine have been at least partially saturated for many years. The mechanism for recharge at both mines is lateral flow from adjacent unmined strata and leakage of water contained in sediment control impoundments (Ringler, 1983). Aquifer tests of wells developed in spoils of the two mines in the regional area indicate that the spoils conduct groundwater at about the same rate as did the coals prior to mining. In general, the TDS concentrations of groundwater in spoils is about 1.5 times greater than premining conditions. The principal constituents in the spoil groundwater are magnesium and sulfate. Lead and nickel are the only trace elements that are generally higher in groundwaters of reclaimed areas than in other areas.

3.6.3 Presentation of Case Study

3.6.3.1 Baseline Data

In regard to both volume and areal distribution, the groundwater database compiled by Van Voast et al. (1977) and used by the mine applicant in the permit application studies is very large. This is in part due to the fact that the mining operation that is adjacent to the one under review may itself eventually disturb approximately 10,000 acres of land. As previously mentioned, the MBMG study was directed at assessing hydrologic conditions within and in the vicinity of both mine sites. Because of the close proximity of the two operations, many of the observation wells developed in the area yielded data pertinent to both mine sites. Development of a large groundwater database was also required since a primary objective of the MBMG study was to determine the existing effects of mining on aquifers by comparing groundwater quality and quantity in mine areas to "baseline" groundwater conditions.

The groundwater data compiled by Van Voast et al. (1977) and utilized in the mine-permit application includes 78 monitoring wells constructed specifically for the mining companies and developed in the five shallow aquifers and in the reclaimed and unreclaimed spoils existing in the area. The monitoring wells were constructed over about a three year period beginning in 1973. About 31 of the wells are located within or adjacent to the mine of this case study, and the remaining wells are within or relatively close to the other mine. In addition, 26 shallow wells were constructed by MSU in the alluvium of one of the ephemeral stream valleys to specifically assess groundwater conditions in a subirrigated field downstream of the applicant's mine-permit area. Four of these wells were apparently also utilized by Van Voast et al. (1977). Of the 78 aforementioned monitoring wells used in the groundwater database, 18 are developed in the spoils. Four of these spoil wells are within the applicant's present permit area or in the area of unreclaimed spoils mined prior to 1973, and the remainder are in reclaimed or unreclaimed spoils of the adjacent mine operation.

Monitoring of water levels in these 78 wells was apparently conducted monthly in all wells and the data were presented on hydrographs. The period of record of water-level monitoring ranged from one to three years, depending on respective well-construction dates. Three spoil wells, one of which is located in the unreclaimed area adjacent to the applicant's existing permit area, were dry throughout the monitoring period.

Assessments of groundwater quality were based in part upon sampling of 47 of the 78 monitoring wells. Sampling was conducted over a three-year period, also beginning in 1973. Some wells were sampled as many as ten times, and the total number of samples was 106. Of the 106 samples, 26 were analyzed for major constituents and trace elements, and the remaining 80 for major constituents alone. Groundwaters in the spoils and in the two coal seams were sampled the most frequently.

In addition to the groundwater monitoring described above, the regional hydrologic investigation by Van Voast et al. (1977) included compilation of basic information for a large number of springs and private wells existing in the area. This inventory included sites as far as 18 miles from the applicant's mine area. Not all of this inventory is presented in the mine-permit application, but the reader is referred to the MBMG report for the complete compilation. The application does contain data on depth to water, well depth, water use, and aquifer supply zone for about 81 private wells. The aquifer supply-zone descriptions are indexed to the stratigraphic intervals of the coal seams at the mines in order to show the correlation with and significance of the data to the mine aquifer zones. Some entries in the private water-well listing also have values of water temperature, specific conductance, or both, thereby providing a reconnaissance-level perspective on regional water-quality characteristics.

Approximately 58 of the springs and private wells inventoried by Van Voast et al. (1977) have been sampled by either the MBMG or the U.S. Geological Survey. The sampling was conducted in 1972 and 1973. The resultant analyses are presented in the permit application and include only major chemical constituents. As previously mentioned, the source of each water is indexed to the stratigraphic intervals of the mine areas. The mine-permit application also presents the analytical results for major constituents of 23 samples of water from mine pits, ponds and streams in the regional area from the work by Van Voast et al. (1977). These latter samples were taken between 1972 and 1976. Trace element analyses are provided for 21 of the 81 samples taken from private wells, springs, streams, and mine pits and ponds between 1972 and 1976.

Information on the historical quality of groundwaters and surface waters in the area is presented by Van Voast et al. (1977) and reproduced in the mine-permit application. This database consists of 15 sample analyses for major chemical constituents as originally reported by Renick (1929). These samples were collected in 1923 and were from wells in various stratigraphic intervals of the Fort Union Formation and possibly the Lance Formation, from wells in alluvial deposits and test bore holes, and shafts in coal seams. One sample is from a water hole in a local stream.

Twenty-two of the aforementioned 78 monitoring wells were tested by Van Voast et al. (1977) to determine hydraulic characteristics of saturated spoils and aquifers in the area of the two mines. The resultant data are presented in the applicant's mine-permit application. Eleven of the tests are of the spoils, nine are of the coal seams, one is of the alluvium, and one is with a well developed in the strata between the two coal seams. Two of the spoil tests are in unreclaimed spoils lying adjacent to the applicant's existing mine area. The permit application also provides an estimate of the transmissivity of the sub-coal sandstone at the mine site as determined from production and drawdown data recorded at the mine tipple well.

In addition to the hydrologic database compiled for the regional groundwater investigation, other monitoring has been conducted and data compiled to conduct specific studies required by the DSL, to acquire more information in regard to surface-water characteristics and to facilitate preparation of the reclamation plan. In summary, these additional efforts have included the installation of flumes, automatic water samplers, crest gages, and controlled stream-channel cross section reference areas to evaluate sediment yield and surface-water flow characteristics of the two streams in the permit area. The monitoring of many of these installations, which began prior to 1981, is still underway. Sixteen neutron-probe access tubes were installed and monitored over approximately a two-year period to evaluate recharge capacity, moisture migration and plant water use in a subirrigated area downstream from the mine-permit boundary. An evaporation pan, wind speed recorder, barometer, two precipitation gages, and a hygrothermograph have also all been installed, and apparently are still monitored, to help evaluate the hydrologic balance of the mine area.

The mining company also sponsored a study of the quality of water in the main stream that is about three miles distant from the mine and to which the streams in the mine are tributary. This study, which was conducted over about a one-year period, involved the collection of 18 water samples at two monitoring sites. The analytical data from these samples are presented in the permit application, although data on streamflow rates during times of sampling are lacking. The permit application also refers to the results of water-quality sampling of this main stream reported in a study conducted by the U.S. Geological Survey (Knapton and McKinley, 1977).

Some of the most significant information relative to the effectiveness of mine spoils in aquifer restoration has been gathered by the applicant subsequent to the submittal of the last mine-permit application amendment (July 1983). Specifically, because of an increased need for water to supply certain mine facilities, the applicant recently conducted a long-term pumping test at a site in reclaimed spoils to determine the feasibility of exploiting groundwater from this source. The test involved one pumping well and six observation wells. The results of the test data indicate that the spoils in that area are apparently much more permeable than the strata that they replace, and are quite suitable for high-yield production of water. Currently, the pumping well used in the test supplies water for mine facilities and is pumped at a rate of about 100 gallons per minute (gpm). The factors contributing to the highly permeable character of these mine spoils are not known, but may be associated with the fact that the spoil materials there are reportedly very sandy and receive recharge from nearby unmined coal.

3.6.3.2 Analytical Techniques

Analytical techniques used in the mine-permit application to evaluate hydrologic characteristics of mine spoils and the effects of mine spoils on local and regional groundwater conditions are generally simple, comparative processes of data analysis. As described earlier for the sources of hydrologic data, most of the analyses were conducted by the MBMG (Van Voast et al., 1977) and are pertinent to the two mines existing in the area. No modeling or other rigorous numerical techniques were applied in the analysis of regional or mine-site groundwater conditions.

The approach utilized in the technical analyses was to develop comprehensive data bases of current and historical information by which groundwater conditions within and in the immediate vicinity of the two mine areas are compared to historical conditions and current conditions in areas distant from the mines. To accomplish this, a considerable amount of information was compiled regarding the stratigraphic positions of aquifers, and the uses and quality of groundwater over a broad, geographic area. Much of this information was derived from the records of water wells and developed springs constructed by the inhabitants of the area, augmented for the purposes of the hydrologic studies by selective water sampling. Some of the database dates back as far as approximately 60 years, thereby providing a good perspective on hydrologic conditions prior to mining. Regional hydrologic data were collectively analyzed to determine arithmetic means and ranges of major chemical constituents in groundwaters, yields and water elevations of specific aquifers, and the temporal and spatial distribution of groundwater mineralization within specific aquifers. Static water levels were plotted on maps and potentiometric-surface contours were drawn to illustrate regional directions of groundwater movement and sources of recharge and discharge within the upper-most coal seam. Maps were also drawn illustrating the quality of water in springs, wells, ponds, and streams.

The groundwater database derived from the monitoring, testing and sampling of observation wells within and near mine areas is variously described and analyzed in the permit application, and the results compared to the regional analysis described above to determine the effects of mining on groundwater supplies and to provide predictions for future groundwater conditions. Some 70 hydrographs are used to identify the relative amount and areal extent of aquifer impacts from mine dewatering, to estimate natural recharge rates to aquifers, and to illustrate recovery of groundwater levels in spoils. In the permit application of this case study, precipitation quantities are compared to gains in spoil groundwater levels to attempt to quantify the vertical permeability of the spoil materials. Perhaps because of uncertainties in this analysis, the applicant committed to a study plan for assessing the vertical permeability of its mine spoils. This plan is described later in this case study.

The quality of groundwater in aquifers in the vicinity of the mines and of the spoils within the mines are compared to regional water quality to further determine the effects of mining. Based upon this comparison, those major and trace-element constituents that are generally higher in mine spoils than in undisturbed aquifers are identified. Temporal variations in spoil-water qualities are described by comparison of the analytical results of samples from old spoils to samples from relatively new spoils.

Assessment of the relative ability of the spoils in the mine areas to transmit groundwater and thereby to restore regional groundwater flow after mining is accomplished by comparison of the hydraulic conductivity values from tests of eleven spoil wells with those from ten tests conducted with wells in bedrock aquifers. The methods of testing and data analysis follow standard techniques. From this comparison it is concluded that the spoils are approximately as transmissive as the coals that they replace, and that, therefore, the reclaimed mine areas will not obstruct regional groundwater flow. Groundwaters in future mine spoil areas are predicted to be chemically similar to those already existing in the area.

The application contains a commitment to selectively place materials determined chemically unsuitable eight feet below ground surface, away from reconstructed stream channels, and above the postmining water table to help prevent the entry of undesirable elements into the groundwater system. As well as those strata determined unsuitable because of natural, pre-existing constituents, the applicant commits to the same special handling of haul road materials that have been treated with magnesium-chloride for dust suppression. Protection of postmining groundwater quality is further provided in the permit application by plans to construct spoil surfaces that are well drained by channels. With this design, the precipitation falling on reclaimed spoil surfaces will have less chance to deeply infiltrate the spoils and thereby potentially leach undesirable chemical constituents into the groundwater system (see Section 2.4.2.4).

3.6.3.3 Monitoring and Reporting

Because of the manner in which the mine-permit application document has been amended and then numerous pages revised in response to DSL deficiency comments, portions of it are very difficult to review. Little information can be found regarding the mine-life hydrologic monitoring plans. One of the latest DSL deficiency comments, in fact, expressed concern that the subject of mine-life hydrologic monitoring is not adequately discussed in the permit application.

From the information found in the permit application, it seems that the mine-life groundwater monitoring program currently followed includes the quarterly or monthly measurement of water levels in some wells, and some quarterly or semi-annual groundwater sampling. It is not known whether or not the monitoring program includes all 53 observation wells that lie within or close to the mine site. Mine personnel indicate that about 7 or 8 new monitoring wells have been constructed in recently-reclaimed spoils within the permit area. The analytical results of all hydrologic monitoring are submitted semi-annually to the DSL and written reports are submitted annually.

The revised permit application also contains plans for specific studies pertinent to aquifer restoration that will be conducted in response to deficiency comments made by the DSL. These plans include chemical analysis of regraded spoils to identify any acid or toxic-forming materials and evaluation of the vertical permeability and recharge capacity of spoils. The applicant contracted the MSU research team to study molybdenum concentrations. To evaluate the vertical permeability and recharge capacity of spoils, the applicant proposes to compare the hydraulic characteristics of spoils with those of undisturbed aquifers. To accomplish this, wells will be constructed in spoils and in "native range" and long-term aquifer pumping tests will be conducted. Groundwater levels will be monitored to determine the barometric efficiencies of the saturated materials. Infiltration rates will be measured at the various sites, and samples of the materials will be taken to determine bulk densities.

From examination of the mine-permit application it is difficult to gauge the adequacy of the proposed mine-life hydrologic monitoring network. The use of a spoil well as a source of mine water supply may provide valuable information with which to evaluate spoil permeabilities, recharge rates and groundwater quality characteristics, although this information must be used with caution in view of the fact that this high-yield spoil well appears to be an anomaly.

3.6.3.4 Evaluation Criteria

As described in Section 2.4.2.3 the hydraulic and water-quality characteristics of spoil materials cannot be predicted with accuracy. Much of the empirical data available today has been obtained at this mine, where spoils have been in place for as much as 15 years. These data indicate that the TDS concentrations in spoil water are about 1.5 times as high as in the undisturbed coal aquifer, and generally lead and nickel are also higher. The applicant has committed to special handling of toxic and acid-forming overburden, although nowhere in the application was there a quantitative analysis of how this will affect postmining spoil-aquifer water quality or exactly what water-quality criteria were being used as a goal from this special handling. Past special-handling techniques included burial of interburden material, which is high in clay content and molybdenum concentrations, on the floor of the pit (Walsh, 1985). The effects of this special handling on spoil-water quality were not analyzed in the application.

In one area of the mine the spoil aquifer is quite permeable, and a spoil well has been installed that can be pumped at a rate of 100 gpm. This appears to be an anomaly, caused by high sand content in this particular spoil area and the position of the well relative to unmined coal, which provides the source of recharge. On the whole, data presented in the application indicate that the spoil material will conduct groundwater at about the same rate as the undisturbed coal. This seems to be an informal criterion for reclamation success, although it is not supported by specific bond-release criteria (see Table 5).

3.6.4 Identification of Issues

The applicant has committed to the special handling of toxic and acid-forming overburden materials in order to enhance water quality in the replaced spoils. Potential benefits to spoil-water quality, however, were not quantified. While economics are not a primary consideration of regulatory authorities, research is needed to quantify spoil-water quality with and without this special handling to determine the environmental benefits and cost-effectiveness and to provide criteria with which to evaluate the success of the special-handling practice.

3.7 Case Study G

3.7.1 Focus

This case study examines the techniques a particular mining company employs to compile, manage, analyze, and utilize a very large hydrologic database. Hydrologic monitoring at the site has been conducted for nearly twelve years, and the extent and diversity of the monitoring is very great by virtue of both the age of the mine and the large area that has been and will be disturbed by mining.

3.7.2 Description of Mine and Hydrologic Setting

The mine that is the subject of this case study is located in southeastern Montana and has been in operation for approximately seventeen years. Prior to the initiation of the current operation, mining was conducted by another entity at contiguous sites for some thirty-four years. By the end of 1980, a total of approximately 4,250 acres of land had been disturbed by the two mining companies. The existing mining company may alone eventually disturb about 10,000 acres of land. The mine is divided into six areas, each having its own discrete permit area and mine-permit application. One area has been entirely mined out, mining is soon to begin at another area, and, at the other four areas, mining is currently underway. Two of the active mine areas lie adjacent to another operating mine which will eventually disturb about 1000 acres.

In order to manage the large volume of environmental data generated by the monitoring of its mine areas each year, the mining company compiled a resource library. The library consists of about sixty-six volumes divided by discipline (hydrology, soils, archaeology, etc.), and each discipline is further divided into resource data and resource reports. Table 10 presents a summary of the types of information presented in the hydrologic resource library.

The most recent permit, approved in 1984, is for expansion of one of the active mine areas to include an additional 2,600 acres of land. Production of coal in this area is projected to be about four million tons per year. The permit application document commonly references hydrologic data contained in the hydrologic resource data volumes as well as pertinent findings provided in various reports contained in the hydrologic resource report volumes.

The mine is located near the northwestern edge of the Powder River Basin. The average annual precipitation is about sixteen inches and the area is classified as semi-arid. Most of the land surface is characterized by gentle slopes; however, resistant sandstone and clinker deposits occasionally form steep slopes and bluffs.

Four ephemeral streams and one small perennial stream drain the mine areas. One of the ephemeral streams is tributary to the larger perennial stream near the mine, and the other three ephemeral streams are tributary to another larger stream about six miles east of the mine. The latter stream is ephemeral upstream of the mine but has a small perennial flow downstream of the mine. The quality of most streamflow is poor and unsuitable for domestic use, but has been widely used for stock watering purposes. No AVFs have been identified at this mine.

Table 10. Hydrologic Resource Data and Report Library, Case Study G

Volume	Contents	Summary of Types of Information Available
Hydrologic Resource Data Library		
I	Hydrologic monitoring site descriptions.	Information on site location, type of installation, period of record, frequency of monitoring, well completion, streamflow quantity and quality data, precipitation data, drawings of monitoring facilities, and agency responsible for data collection.
II	Groundwater levels.	Tabulated values of water elevations in monitor wells for period of record.
III	Groundwater data.	Hydrographs of groundwater levels, aquifer-test results, water-quality data.
IV, V	Well logs.	Lithologic logs of all monitor wells.
VI	Well development data.	Development data for monitor wells, including development technique, duration, initial and final water levels, approximate well yields, and observations of turbidity.
Hydrologic Resource Report Library		
13 volumes	Monitoring data and reports.	Annual and interim hydrologic monitoring reports, correspondence relating to hydrologic issues, reports on hydrologic investigations separate from monitoring programs, and AVF reports. These reports are authored by personnel of the mine operator, consultants, and research agencies.

Three coal seams, all in the Tongue River Member of the Fort Union Formation, have been identified in the mine areas. Only the uppermost seam, which averages about 25 feet in thickness, is mined. Overburden is removed by dragline. The lower two coal seams, which are separated by a thin shale layer, are not mined because of poor quality, excessive depth, or both. The upper seam, as well as the middle seam, are both mined at an adjacent operation.

The bedrock strata in the mine dip gently (1 to 2 percent) to the south-southeast. The upper coal seam crops out and has burned at numerous sites within the mine areas. The bedrock units above and below the upper coal consist primarily of shale and sandstone, and clinker deposits from coal burns are common on the land surface. Old, unreclaimed mine spoils are present at several sites within and adjacent to one of the mine areas.

In addition to portions of the old mine spoils, five shallow aquifer zones have been identified in the mine areas. These include the alluvium of the principal drainages, sandstones in the coal overburden, the upper two coal seams, and a sandstone underlying the lowermost coal. All have historically been widely exploited as sources of rural-domestic or stock-watering supplies. The alluvial aquifers are the most transmissive, but generally have poor groundwater quality. The coal aquifers are usually much less transmissive than the alluvium, but often have better water quality. The quality and yield of groundwater from the sandstone aquifers is highly variable due to the fact that the sandstones are discontinuous and of variable composition. The sub-coal sandstone is generally a good producer and it supplies numerous private and industrial supply wells in the area.

Over most of the mine area, the upper coal seam and overburden are well drained by entrenched stream channels. Groundwater inflow rates to most mine pits have been relatively small. Van Voast et al. (1977) predicted that most future mine cuts will intercept little groundwater due to the low permeability of the aquifers and because, over broad areas, the upper coal seam is dry or only partially saturated. Larger inflow rates may occur where mine cuts approach or intercept old, saturated mine spoils. Large reductions in water levels of the upper coal seam and coal overburden are expected within and in the immediate vicinity of some mine areas due to mine dewatering; however, based upon results of groundwater monitoring reported by Van Voast et al. (1977), water-level declines through 1976 were negligible.

3.7.3 Presentation of Case Study

3.7.3.1 Baseline Data

The mining company conducts hydrologic monitoring (see Section 3.7.3.3) within and in the vicinity of its six mine areas and the volume and diversity of data generated by this work is exceedingly large. The hydrologic resource library examined in preparation of this case study (see Table 10) contains all of the monitoring data in a clear, concise format. This minimizes the confusion commonly associated with many permit application documents wherein supporting data are difficult to find if provided at all.

Data presented in the hydrologic resource data library includes:

1. precipitation data from 19 stations,
2. aquifer-test results for 173 monitor wells,

3. several hundred water-quality analyses including analyses of samples collected by the U.S. Geological Survey, the MBMG, and the mine operator from 151 wells,
4. surface-water quality and quantity data from 34 stations on five streams as well as sampling sites on 5 ponds, all active pits and other sources of standing or discharging mine waters,
5. static water-level measurements taken quarterly in 507 regular monitor wells and 51 temporary monitor wells, and
6. water-quality analyses for samples taken from 214 wells, each of which is sampled at least annually.

Considering that the surface-water monitoring stations have periods of record ranging up to 6 years and the groundwater monitoring wells have periods of record ranging up to 12 years, and considering the large number of parameters measured (refer to Section 3.7.3.3), it can be seen that the database is very large and complex and is growing rapidly.

The hydrologic resource report library (Table 10) is a library of reports on hydrologic investigations in the area, not all of which were conducted at this mine. In general, the hydrologic study reports provided in the hydrologic resource report volumes deal with many subjects pertinent to the hydrology of the mine and regional area. These subjects include: analysis of alluvial valley floor characteristics; potential impacts from coal-fired power plant waste waters; selective placement of strip mine overburden; waters impounded on mine spoils; regional and mine-site hydrogeologic analyses with projections of potential mine impacts; postmining spoil water quality; and water infiltration rates of disturbed and undisturbed lands. These reports were variously authored by private consultants, the Montana Bureau of Mines and Geology, investigators from Montana State University, and personnel of the mining company.

3.7.3.2 Analytical Techniques

Plans provided in the permit application to control and treat surface-water runoff from disturbed areas are based upon standard analytical techniques. Peak runoff rates for channel and ditch designs were computed using the Johnson-Omang (1976) or SCS (1972) triangular hydrograph method (see Section 2.3.2.1). Where the SCS method yielded results within 50 percent of those calculated by the Johnson-Omang technique, the SCS computational results were used in the designs. Where the difference between the computational results of the two methods exceeded 50 percent, the average value of the two results was used. Runoff volumes for pond designs were estimated using the SCS method only. Sediment-storage volume requirements for some ponds were computed using the constant sediment delivery ratio quoted in the State rules and regulations. For other ponds, required sediment-storage volumes were based upon solution of the Universal Soil Loss Equation and an estimated sediment delivery ratio. The slopes and configurations of channels and ditches were designed using the Manning equation. The operator commits to using rock riprap where channel velocities will exceed a specific value.

Two streams will receive minor discharges of treated water from the mine. The quality and quantity of flow in the streams and the probable impacts from mine discharges are described by reference to monitoring data presented in the hydrologic resource data library.

Little information is provided regarding the premining or postmining geomorphic characteristics of the stream channels. In response to comments made by the DSL, the reclamation plan was revised to increase the diversity and drainage density of the postmining topography.

The quality of groundwater in various aquifers within and in the vicinity of the mine area is described by reference to data presented in the hydrologic resource data library. Aquifer hydraulic characteristics are described by reference to aquifer-test data presented in the library. The aquifer testing was done by conventional methods and included pumping tests, bailer tests and slug-injection tests. The flow of groundwater in aquifers was estimated through solution of the Darcy equation using observed groundwater gradients and average values from the aquifer test results. The quantity of groundwater stored in aquifers is estimated by reference to textbook values for similar aquifer lithologies and hydrologic conditions, and by an approximate method based on aquifer thickness described by Lohman (1979). The application refers to the library for other groundwater quality and aquifer test data collected in the area by Dollhopf et al. (1977) and Van Voast et al. (1977).

The quality of postmining groundwater in spoils is estimated by a technique developed by Van Voast et al. (1978) using geochemical data from twenty-two overburden holes in the mine area (see Section 2.4.2.4). The results of aquifer tests conducted in spoils of the mine areas by Van Voast et al. (1977) are referenced in the application, and the reports are included in the report library. The results of work conducted by other investigators at the mine site and at other mines in the western United States (Arnold and Dollhopf, 1977; Schafer et al., 1979 and Moran et al., 1979) are referenced in description of the approximate infiltration rates of the postmining spoils. Again, referenced reports are provided in the report library.

Probable impacts to aquifers during mining are not quantitatively assessed in the permit application but are approximately described by reference to conclusions made by Van Voast et al. (1977) in a hydrogeologic study of the mine site and regional area.

Chemically or physically unsuitable overburden materials are identified in the permit application through the analysis of geochemical data from forty-eight drill holes in the proposed permit area. These materials are assumed to be mixed with suitable materials during mining and no special overburden-handling program was presented.

3.7.3.3 Monitoring and Reporting

Surface-water monitoring at this mine consists of:

1. maintenance of 12 recording stations and 34 crest-stage gaging stations, some with automatic samplers. Water samples are collected when flows occur at the 12 recording stations,
2. daily measurement of flow from all pond discharges and monthly sampling of these discharges for chemical analysis,
3. quarterly sampling of water in non-discharging ponds for chemical analysis, and
4. annual sampling of water in mine pits for chemical analysis.

Groundwater monitoring consists of:

1. quarterly water-level measurements in 507 wells (and occasionally in another 51 wells),
2. maintenance of continuous water-level recorders in 17 monitor wells, and
3. annual sampling of water from 214 wells for chemical analysis.

The data from the monitoring program are submitted to the regulatory authority semi-annually as updates to the hydrologic resource library.

3.7.3.4 Evaluation Criteria

Some of the earliest concepts of groundwater restoration at western surface coal mines were developed from information obtained at this mine, due in part to the age of the mine and the hydrologic database assembled by the operator and the MBMG. In 1977 it was reported (Van Voast and others, 1977) that:

1. Similarities in aquifer transmissivities and hydraulic conductivities in the spoils and undisturbed Fort Union aquifers imply that postmining flow rates through the spoils should not be greatly different from those before mining. Therefore the reclaimed spoils will not act as barriers to groundwater flow.
2. Leachates from spoils will probably have dissolved-solids concentrations ranging between 1,000 and 5,000 mg/l, which means that the water will remain within the range considered suitable for livestock (see Table 1).

3. The general quality of groundwater in the mined areas will ultimately alter to become more representative of waters in other non-coal aquifers, which are generally more mineralized than waters from coal beds.

Because of a lack of established numerical criteria for groundwater restoration (see Section 2.4.3 and Table 5), these concepts and the supporting data are referenced in numerous permit-application documents in support of, and in some cases in place of, analytical methods to predict spoil-aquifer characteristics and the groundwater impacts of mining.

As described in this case study the hydrologic database continues to expand at the mine. Specific programs are not described in the application for all the monitoring being conducted, but presumably the data will continue to be used to refine certain predictive techniques. The applicant has proposed, in the application document, to help fund a study with MBMG to refine a technique developed by Van Voast et al. (1978) for predicting spoil-water quality for specific application to this mine area.

A large percentage of the surface and groundwater monitoring installations currently included within the mining company's monitoring network were installed by or for research agencies conducting independent hydrologic studies in the area. In some cases these agencies are still participating in the monitoring and data analysis; thereby they presumably have some input in revising the monitoring plans as mining continues to disturb ever-increasing areas.

Mine personnel report that some logistics problems have arisen in the updating and use of the hydrologic resource library. The mining company has significantly expanded the library over the last several years. Problems have occurred when references to the library in the permit application documents have been outdated by the periodic revisions to the library. The solution employed by the mining company thus far has been to include with the library revisions cross-reference tables indicating the relationships between titles in old and new tables of contents. This technique has not been entirely successful as the DSL has expressed some confusion in attempting to find supporting hydrologic data when reviewing the mine-permit applications. In some cases this confusion has reportedly been manifested by the DSL issuance of permit application deficiency comments requesting supporting hydrologic data.

3.7.4 Identification of Issues

This mine had the largest hydrologic database of any mine studied in this investigation. Due to its age and the amount of research that has been conducted at this mine, it also has more data on spoil-aquifer characteristics than any mine studied. By comparison with a new mine, it would seem that substantial data are available on which to base decisions regarding the probability of successful groundwater restoration. Ironically, however, the mine also has the most extensive hydrologic monitoring program of any mine studied. Also, the applicant has proposed to fund more research in order to predict postmining water quality. One issue seems to be what amount of monitoring and data collection will provide sufficient information to evaluate reclamation success or the probability thereof. Also, if this mine has insufficient information for the above purpose, on what basis are permits for new mines issued? Another issue, considering the size of this mine's hydrologic data base, its rate of growth, and the number of other mines with similar, though less-extensive monitoring programs, is that some program will have to be developed to manage and evaluate the enormous amount of data that will be submitted to regulatory authorities in the coming years.

3.8 Case Study H

3.8.1 Focus

This case study examines the hydrologic issues associated with a mine situated adjacent to a major river and reservoir, both of which are sources of irrigation water. Both surface and groundwater issues are addressed in this case study. This case study corresponds with Case Study D in the Soils and Overburden report (Walsh, 1985).

3.8.2 Description of Mine and Hydrologic Setting

The mine is located in southern Montana and is permitted for about 1,100 acres of mining, 235 acres of spoil and ramp roads and 1,900 acres of associated disturbance. The operator has been mining since 1972, with a current production rate of eight million tons per year.

The mine is located in the northern part of the Powder River Basin. Mineable coal beds in the area are the D-1 and D-2 coal beds of the Tongue River member of the Fort Union Formation.

The climate in the mine area is the continental steppe type typical of the Northern Great Plains area. It is semiarid and characterized by cold winters, warm summers and a large variation in annual and seasonal precipitation. Average annual precipitation for the area is approximately twelve inches of which about 45 percent falls in the three-month period from April through June. An additional 30 percent falls mostly as snow in the six-month period from October through March and the remainder generally occurs as summer thunderstorms. Most flooding in small streams in the area occurs in response to high-intensity thunderstorms of short duration.

Three surface-water systems are of interest in or near the mine site: 1) the reservoir located on a major perennial river within a few hundred feet from the mine area, 2) the mine discharge, and 3) an ephemeral stream and its tributaries. The major perennial river originates in the Big Horn Mountains and flows northeastward through Wyoming and into Montana.

The reservoir, built in 1939, covers 3,500 acres at full capacity and controls the base level for shallow groundwater aquifers from the mine area. Water quality in the reservoir is similar to that in the river, which the Montana Department of Health and Environmental Sciences has classified as suitable for drinking water if it is adequately treated.

The mine is in the lower reaches of an intermittent stream drainage. The permit area ranges from 3,420 to over 3,700 feet in elevation. Natural slopes range from less than five percent to over 50 percent. Many of the upland areas exhibit badland characteristics, having steep slopes and little vegetation. The northeastward-flowing river and the reservoir, which are the base level for all streams draining the region, are the dominant geomorphic features.

Within the mine area, the coal seams and the clinker from the coal burn are the major sources of groundwater of usable quality. Most of the coal aquifers in this area are artesian. Adjacent to the area, the river alluvium is a source of good water. Groundwater in the vicinity of the mine is obtained from coal seams for both stock and domestic use. These aquifers are below the coal seams to be mined and are viable alternatives for a source of water if other water supplies are impacted by mining. Other potential aquifers within the permit area contain little or no water and are of limited areal extent. These include the alluvial deposits of intermittent streams, the clinker-capped hills in the northern and southeastern corners of the permit area, the thin river-terrace deposits at the extreme southeastern limits of the permit area, and discontinuous sandstone lenses in the overburden and interburden.

Inhabitants of the area near the mine are heavily dependent upon groundwater for stock and domestic purposes. The operator withdraws water from two wells and from the pit to meet various operational needs. One of the industrial wells is completed in the lower coal aquifers while the other well is completed in an overburden sandstone and the upper coal aquifers.

3.8.3 Presentation of Case Study

3.8.3.1 Baseline Data

A monitoring-well network was established in 1970 by the MBMG. Groundwater data from those wells have been published by Van Voast (1974), Van Voast and Hedges (1975), Van Voast, Hedges, and McDermott (1978), and the United States Geological Survey. These data sources were included in the permit application.

Potentiometric-surface maps were prepared for the coal aquifers in and adjacent to the study area using water-level data collected by the applicant, MBMG, and various other research and university organizations. Aquifer properties, including transmissivity and hydraulic conductivity, were determined from pump tests conducted by the applicant.

Water-quality data were collected from monitoring wells throughout the area. Data on water quality in the coal aquifers, clinker aquifers, and the alluvium have been collected since 1974. Parameters evaluated include TDS and all major cations and anions. Water-quality data have also been collected for the pit influent and analyzed for dissolved constituents to determine if significant inflow from the nearby alluvial system is occurring.

Monitoring wells have been established in the mine spoils to collect data on aquifer reestablishment within the spoils. Pump tests have been conducted to determine the hydraulic properties of the spoil aquifer. Water-quality samples from the spoil aquifer have been analyzed to provide a database for comparison with premining water quality.

Pump tests were conducted in the study area to determine spatial variability in coal-aquifer properties including transmissivity and hydraulic conductivity. Reported yields and quality of water from deep wells completed in multiple coal seams below the coal seam to be mined were examined to determine the availability of alternative water supplies in the event that impacts to existing wells resulted from mining.

Information is being collected to characterize the premining surface-water system at the mine. The information requested by the Montana Department of State Lands (DSL) includes relief ratios, drainage densities, channel slopes, valley and flood-plain slopes, channel sinuosities, channel lengths, drainage areas, pictorial surveys, surveys of channel cross sections, and textural analyses of bed and bank materials. The surveyed profile, cross section locations, and pictorial survey of each cross section can be found in the permit application package.

Three locations were selected within the mine boundary for surveyed cross sections of stream channels. Two pictures were taken at each cross section location, one showing the flood plain and the other showing the incised channel within the flood plain. Roughness coefficients were estimated for different stages of flow at each section and are provided with the pictorial survey.

Hydraulic data for each surveyed cross section presented in the application included the slope, the roughness coefficient, the average depth of flow, the Froude number, and the velocity for the peak discharge computed to result from the 100-year, 24-hour precipitation event.

Field data collected for the premining drainage basins included vegetation communities, number of head cuts, number of stockponds, springs, areas of subsidence or depression, and texture of stream beds and banks.

Geomorphic characteristics which were calculated include (Chow, 1964):

basin relief
basin perimeter
basin area
stream length
maximum basin length
average basin width
drainage density
form factor
compactness coefficient
circularity ratio
elongation ratio
ruggedness number
mean basin elevation
mean basin slope
length of overland flow

The geomorphic variables were determined from field surveys and a USGS topographic map with a scale of 1" = 2000' and a contour interval of 20 feet. The drainage areas of interest were determined whenever possible using a 1" = 500' scale topographic map. Larger drainage areas were determined from USGS maps.

3.8.3.2 Analytical Techniques

The Darcy equation was used in conjunction with a flow net to estimate pit inflows from the aquifers and interactions between aquifers. The main technique used to define the impacts on the groundwater system was the monitoring of wells in the area which were designed and constructed for that purpose. Monitoring of the groundwater system over time was used to show development of the cone of depression around the pit.

Peak flows for ephemeral channels were computed using the SCS triangular hydrograph method (see Section 2.3.2.1). The soils within the mine boundary were classified, planimetered, and divided into hydrologic soil groups A, B, C, or D for determination of the curve number (see Section 2.3.2.1).

The operator has recognized the need for a properly designed and constructed reclaimed stream channel system. However, as a stipulation to the permit, the surface water drainage design was to be submitted within two years of approval of the permit. The analytical techniques to be used in design of the reclaimed stream channels are not discussed in the permit application.

3.8.3.3 Monitoring and Reporting

The original groundwater monitoring system was expanded to the present network, which includes 105 monitor wells, in 1975. This network is presently maintained by MBMG with active monitoring of the system also conducted by the operator. An analysis of the well network and monitoring schedule was begun in response to regulatory changes related to approval of the state program. Wells within the permit and adjacent areas are monitored on a monthly basis for water-level change by the operator and MBMG. Continuous recorders have been installed on at least one well in each aquifer affected by mining.

The groundwater monitoring plan shows eight wells that are used to monitor groundwater quality around the mine. Three wells are completed in the upper coal, two in the lower coal, one in the coal below the lowest seam to be mined and two in the resaturated spoil. Water-quality sampling is done semi-annually, in the spring and fall. Samples are taken after the wells are pumped until the temperature and conductivity stabilize and analyzed for required parameters (see Table 4). Water quality data are submitted to DSL semi-annually. The groundwater monitoring program was designed to detect changes in groundwater quantity and quality resulting from mining activities.

Runoff within the mining area is collected in sediment ponds and discharged at central points under an NPDES permit. Flow rates are continuously monitored, and water-quality sampling and testing are conducted monthly. According to the application this monitoring network will be expanded to fully evaluate the surface-water conditions as reclamation progresses. The operator was required, in a permit stipulation, to submit to the regulatory authority the locations and types of gages used for monitoring streamflow in the ephemeral stream at the west end of the permit area. As this plan was not included in the permit application found in the OSM library, it was not evaluated.

3.8.3.4 Evaluation Criteria

As stated in the permit application, evaluation of the success of reclamation of the groundwater system is to be based upon the monitoring program described in the previous section. The MBMG has established 12 wells within the spoils to monitor water levels and water quality. Water levels are monitored to observe the resaturation of the spoils. Water-quality testing is also conducted at regular intervals to measure changes in water quality as saturation levels rise. No numerical criteria were presented in the application with which the monitoring data will be compared to determine success of the groundwater restoration.

The water-quality network is evaluated on an annual basis to determine if additional wells should be added to the testing. Wells utilized for monitoring are selected based upon the aquifer to be monitored, accessibility, and the anticipated life of the well. Sites selected are not changed unless the well fails and the data are no longer representative of the aquifer.

The success of reclamation of the restored surface-water drainage system is also based upon a monitoring program. The applicant states that runoff from the reclaimed areas will be less than premining runoff due to reduction in slopes and a corresponding increase in infiltration. Sediment ponds are installed below the reclamation areas to maintain discharge-water quality and to serve as a measuring point to evaluate stabilization of reclamation. The applicant anticipates that data collected can be compared to existing data from adjacent undisturbed areas to more fully evaluate the effects of mining. No discussion was provided in the permit application to document whether sufficient data exist or will exist for this approach to be valid. No criteria were presented to evaluate the success of reclamation based on the comparison.

The operator is currently developing a study plan which will address the above areas. This program will potentially include runoff plots, erosion pins, and slope-profile surveying on disturbed and undisturbed sites. This proposed study will be submitted to DSL in the near future for review.

3.8.4 Identification of Issues

Review of the application indicates that there may be redundancy in data collection, since the same wells are monitored by the applicant and the MBMG. Although the agency and the company probably use the data for different purposes, it seems that the process would be more efficient with a single data-collection effort and sharing of the data.

The application indicates that hydrologic restoration is being evaluated through monitoring. While extensive monitoring is conducted, it is not clear how the data are being used to evaluate the probability of successful restoration. Groundwater-level and quality data are compared with baseline values, but a return to baseline conditions or to approximate baseline conditions is not stated to be a success criterion. The bond-release criterion (whether pollution is occurring or will occur, see Table 5) has not been defined since pollution has not been quantified in this context. Therefore there is no concrete way to evaluate whether sufficient data exists or will exist to evaluate the success of restoration. Groundwater data from this mine have been utilized to prepare at least four research papers (Van Voast, 1975; Van Voast and Thompson, 1982; Ringler, 1983; and Davis, 1984) but it is not clear how the data will be used to evaluate reclamation success.

Surface-water restoration is also based upon a monitoring program (see Section 3.8.3.4). However, no design for the reclamation of the surface-drainage system exists, so there is nothing against which to compare the monitoring data to determine if restoration is being achieved. Montana regulations (Rule 26.4.634) are the most specific of any state's regulations regarding reclamation of drainages, and yet the permit was issued without this design being in the application.

The Federal Decision Document states that the reestablishment of steady-state groundwater flow could take as long as 100 years. It was not stated who made this determination or how it was made. However, it raises the question of when any evaluation criteria that are developed will be applied, considering the bond-evaluation period of 10 years (Rule 26.4.1103).

3.9 Case Study I

3.9.1 Focus

This case study examines alternative sediment-control technologies at a surface coal mine in southern Wyoming. The OSM required that the alternative sediment-control program be approved as an experimental practice.

The mine that is the subject of this case study has been in operation for about 12 years, predating SMCRA by some four years. Mining is projected to continue through the year 2020. The permit area is over 20,000 acres in size, of which about 10,000 acres will be disturbed. At the time the alternative sediment-control plan was proposed (1982 annual report), a total of about 3600 acres of land had been disturbed by mining. Of this, only 612 acres will be in the area covered by the alternative sediment-control program due to limitations imposed with approval of the experimental practice.

Because of the large area and high drainage density, the company's life-of-mine sediment-control plan would require the construction of about 200 conventional sediment-control ponds. When sediment-control ponds are constructed, they become point sources of pollution, and are subject to stringent effluent limitations for pH, suspended solids, total iron and total manganese. These suspended-solids standards are exceeded in the natural flows of the streams in the area, which are ephemeral. Natural sediment concentrations range from 400 to 1 million mg/l based on data obtained using single-stage sediment samplers. Effluent standards for TSS from point sources are 70 mg/l (instantaneous maximum) and 35 mg/l (average).

Because of naturally-high sediment loads in area streams and the cost and large number of ponds required for conventional sediment control, the company requested an exemption to the use of sediment-control ponds under the provision of Wyoming Department of Environmental Quality Land Quality Division Rules and Regulations Chapter IV, Section 3.g.(1). This regulation states that exemptions to the use of sediment-control ponds can be granted where, by the use of alternative sediment-control measures, mine drainage will not degrade receiving waters. This exemption was granted by the State of Wyoming after reviewing the company's plans for alternative sediment-control measures. However, the OSM determined that approval of the alternative sediment-control practices could not be given except as an experimental practice because it is based on a premise that differs from the effluent standard contained in 40CFR 434.53 specifying a point source effluent discharge performance standard. OSM regulations incorporating the EPA effluent standard state that the best technology currently available is sediment ponds using a point source. The state regulatory authority approved the alternative sediment-control practice to test the basic hypothesis, as stated in the State Decision Document, that alternate sediment-control techniques are more, or at least as, environmentally protective as sediment ponds. In the State Decision Document this is interpreted to mean that receiving-water quality will not be degraded.

This case study examines the data and analytical techniques used by the applicant to justify and design the alternative sediment-control practices, the monitoring that will be employed to document the effectiveness of the practice, and the criteria established by the regulatory authorities to evaluate the proposed practice.

This case study corresponds to case studies WY-3 in the Vegetation report (Western Resource Development Corporation, 1985) and I in the Soils and Overburden report (Walsh, 1985).

3.9.2 Description of Mine and Hydrologic Setting

The climate of southwest Wyoming is semi-arid to arid, with cold winters and short, warm summers. Poor runoff-water quality naturally results from intense rainfall, low vegetation density, erosive soils, unstable incising stream channels and extremely transient, highly peaked streamflow. The majority of runoff occurs during spring and early summer as the result of intense thunderstorms. These storms deliver high rainfall energies over small areas to the relatively bare soils, and runoff may be restricted to only short reaches of stream. Abundant sediment production occurs from various sediment sources, such as: sodium deflocculated soils, badlands, and channel and gully banks. Influent streambeds concentrate suspended material in the flow as water infiltrates into the streambed. These high rates of sediment production and influent streams lead to high suspended-sediment concentrations during thunderstorm runoff.

At this surface coal mine, receiving waters are local ephemeral streams. The company proposes to utilize alternate sediment-control techniques, in conjunction with a few sediment ponds, to treat disturbed area runoff in order to prevent degradation of local surface-water quality. Alternate sediment-control techniques, such as check dams, straw dikes, and similar structures, had previously been utilized at this mine to conserve soil resources (i.e., trap the sediment near the site of disturbance). Existing natural surface-water quality data and site inspection indicated to the company that alternate sediment-control techniques should preclude degradation of receiving streams considering the local semi-arid hydrology and sedimentology and the high natural TSS concentrations in local streams. It was therefore the opinion of the company that sedimentation ponds were not required to treat disturbed-area runoff in order to protect receiving-water quality. The company designed an alternative sediment-control plan that would include mulching, contour plowing, diversions, check dams, vegetative buffers, and diversion of runoff into the pit. An integral part of this plan is a monitoring program which will aid in determining the effects of mine runoff on receiving stream-water quality if treated solely by alternate-control techniques. Hydrologic and sedimentologic monitoring will be conducted at those points where disturbed-area runoff flows into receiving streams.

Alternate techniques will be implemented on an experimental basis to investigate whether they provide equal or superior environmental protection to sedimentation ponds. They will continue to be implemented throughout the life of the mine.

The objectives of the alternative sediment-control plan are to protect water quality, conserve soil, and reduce mining costs. Under the authority of State and Federal regulations, the company plans to implement adequate and effective alternate sediment control for areas disturbed by strip mining in order to achieve the goals listed above. In addition to the plan objectives, the company stated that there would be environmental advantages to the alternative sediment-control plan. Channel degradation below dams, produced by the discharge from sediment ponds of unnaturally clear and therefore erosive water, would be eliminated. Additional disturbance of more than 400 acres of land due to the construction of sediment ponds would not be required. Through the elimination of impoundment storage, seepage and evaporation, there will be less disruption of natural streamflows under the alternative sediment-control plan.

3.9.3 Presentation of Case Study

3.9.3.1 Baseline Data

Existing data on total suspended solids (TSS) concentrations in local streams were used both to justify the use of alternative sediment-control practices and to design the alternative sediment-control program. Because all the area streams are ephemeral, the amount of available data was limited. Based on 21 samples of water collected in single-stage sediment samplers on five local streams, the company was able to show that for peak monthly discharges ranging from 3.5 to 350 cubic feet per second, TSS concentrations ranged from 400 to 1 million mg/l, compared with point-source effluent standards of 35 to 70 mg/l.

By the time that final design of the alternative sediment-control plan was prepared, the company had collected more data, and a total of 33 data points were available on which to base the design of the alternative sediment-control plan. The arithmetic mean of these 33 TSS values was 30,000 mg/l. This value was used in the design to locate and size alternate control structures. The actual impact of the mine runoff will be determined solely from data collected from the monitoring program described later in this case study.

3.9.3.2 Analytical Techniques

The company will utilize the alternate sediment-control techniques described below to control runoff from mining disturbed areas. In addition, four sedimentation ponds are included in this plan at points where alternate sediment-control techniques are not cost-effective.

Various techniques will be utilized to reduce sediment production and enhance deposition of sediments eroded from disturbed lands. These techniques will require no individual designs with the exception of small channels which will be designed to meet regulatory agency requirements for short-lived diversions. An integral part of the program is the monitoring system described in Section 3.9.3.3.

The alternate sediment-control techniques proposed in this application can be summarized in two categories. First, there are preventative measures, which can help maintain the sediment production at or below the level produced from undisturbed terrain. One example of preventative measures is the use of topographic design of reclaimed slopes to control sediment. Complex slopes with upper convexities, middle straight reaches, and lower concave reaches have long been associated with the lowest erosion rates (Carson and Kirby, 1971). This, in concert with drainage-basin design to provide adequate drainage density and shorter slope lengths, will minimize long-term sediment production from reclaimed lands. Other preventative measures include revegetation, mulching, contour plowing, and utilizing rocky topsoil. Revegetation adds soil strength and surface roughness, retarding flow velocity of overland runoff. Mulch retains surface water, enhances infiltration, and adds surface roughness. Contour plowing also adds surface roughness and enhances infiltration. Rocky topsoil produces an armor when it is eroded, and this armor impedes further erosion (Utah Water Research Lab, 1976).

Second, remedial designs for actively disturbed and temporarily unstable lands can be constructed, where needed, at low cost and with minimal added impact. These techniques include small diversion channels, porous rock or straw bale check dams, interceptor ditches, vegetative buffers and diversion of runoff into the pit. Small channels divert runoff away from sensitive areas. Rock check dams and straw bale dikes act as temporary, permeable barriers to decrease streamflow velocity and cause the sediment load to be deposited. Interceptor ditches are small, level trenches running across the hillside which slow surface runoff and promote sediment deposition. Vegetative buffers are strips of undisturbed (native), vegetated land adjacent to disturbed land. The vegetation enhances sediment deposition and inhibits further erosion. Ditches have been placed around the toes of all topsoil and overburden stockpiles to capture sediment as close to the source as possible. The mine has recently applied for a permit revision emphasizing farming techniques over toe ditch construction, however.

In order to rigorously apply the above techniques to the disturbed areas, a design method was developed by the company using an industry-standard computer simulation model. This method simulates runoff from an area and also simulates the effect of a variety of sediment-control techniques. The sizes and locations of the controls can then be evaluated to best reduce the sediment discharge to levels below the receiving-stream water quality. By using this design method, it is not necessary to have an actual runoff event in order to determine problem areas. The monitoring program (Section 3.9.3.3) will be used to determine the effectiveness of the control techniques as well as record any water-quality degradation which may occur.

Because the objective of the alternative sediment-control program is non-degradation of the receiving stream, a working definition was developed. After consultation with the regulatory authority, the largest ephemeral stream in the area to which all streams within the permit area are tributary was designated as the receiving stream. The receiving stream is not currently truncated by the pit; therefore, changes in through-flowing water quality can be observed at sites above and below the disturbed area. Alternate sediment-control techniques will be used in all areas draining to these sites.

In-stream flow criteria were established to provide a clear definition of stream water-quality degradation. NPDES requirements for point-source discharges (40CFR 434.40) specify limits for iron, manganese, pH, and TSS. Though this plan for alternate sediment control deals with non-point source runoff exclusively, the point-source parameters were used as a guide from which to select a non-point source water quality parameter or parameters. Existing surface-water quality data showed that TSS was the only parameter in natural streamflow which consistently violated NPDES criteria, and therefore TSS concentrations were used as the design parameter for the alternative sediment-control program.

The computer model selected for use in the design of the alternate sediment control measures was SEDIMOT II (see Section 2.3.2.1), developed by the Department of Agricultural Engineering at the University of Kentucky (Wilson and others, 1980) specifically for the evaluation of hydrologic and sedimentologic runoff from areas that have been surface mined. It was assumed that, since this model is an industry standard and is in the public domain, the validity of the algorithms used and the assumptions made has been verified. The regulatory agency concurred with the use of the model and the applicant was not required to provide documentation on the model itself. Due to lack of data, it was not possible to calibrate the model to each individual drainage evaluated.

In the model the SCS curve-number technique is used for water runoff calculations; the Modified Universal Soil Loss Equation is used for sediment calculations; the Muskingum method is used for water routing, and Williams Model I and Yang's unit stream-power equation are used to route sediment in channels and overland, respectively. Computer application of these techniques allows temporal and spatial variability to be incorporated into the analysis. Numerous channel segments and subwatershed areas were specified individually to simulate their individual inputs to the total basin output and to determine the sensitivity of total basin output to changes in particular areas.

Computer simulation using the SEDIMOT II design model was undertaken on nine separate areas. These areas included all disturbed areas to be treated by alternate sediment-control techniques.

The goal of this computer-assisted design procedure was to obtain computed water quality (suspended-sediment concentration), via alternate sediment-control techniques, within the limits of the selected design standard (30,000 mg/l). Successive computer iterations are conducted and additional sediment controls are added as necessary until the design TSS concentration is achieved.

Critical input data for erosion calculations in SEDIMOT II are the particle-size distributions of native and disturbed soils. Initially in this investigation, existing reclaimed-area grainsize distribution analyses were scrutinized, and rough averages were used. Most of these data are for regraded spoil and not respread topsoil. These analyses were based on the fine soil portion only (less than 2.0

mm); the coarse fraction was ignored. In those modeled areas where use of initial data resulted in high computed TSS values, more site-specific data on particle size gradation were gathered.

The simulation techniques used in the SEDIMOT II model are commonly applied at surface coal mines. Use of the computer allows rapid, accurate analysis so that larger areas can be simulated in greater detail and over shorter time steps than by hand techniques.

USLE parameter values and curve number values used in the SEDIMOT II runs were obtained from nomographs in Barfield, et al. (1981) using site-specific soil data. Averages of these data were calculated as averages of reclaimed-area soil samples and undisturbed-area soil samples. The 10-year 24-hour precipitation event was used as the design storm.

In each watershed simulation, a control run was conducted with no control structures. Depending upon the computed TSS concentration, successive runs were then conducted, adding sediment-control structures as necessary until the results showed mean TSS concentrations to be less than the selected design value of 30,000 mg/l. Control structures were added in the following order: rock check dams, contour interceptor ditches, contour berms, vegetative buffer strips, toe ditches, temporary barriers, and benches (on stockpiles).

For the nine areas modeled, it was determined that four required no control measures to limit mean TSS concentrations to values less than or below the design value of 30,000 mg/l. Toe ditches and check dams were adequate for three of the areas. Two watersheds required contour ditches and/or contour discing to meet target TSS concentrations.

The alternative sediment-control plan described above was submitted to the regulatory authority for approval on December 30, 1982. It was approved by the state regulatory authority on July 6, 1983 and by the OSM on July 27, 1983. In addition to the sediment-control plan itself, the company was required to submit for approval a maintenance plan and a monitoring plan as integral parts of the overall program.

All alternative sediment-control structures are required to be inspected monthly and following each rainstorm. Check dams are individually inspected; other structures are visually inspected by road tours. Repairs to any structure must be made as soon as machinery can be safely and effectively operated. All such activity must be recorded in the daily mine log. An unusually large number of runoff events have occurred since the alternative sediment-control plan was approved. While this has provided the opportunity to collect a substantial amount of data through the monitoring program described in the next section, it has also necessitated a substantial amount of maintenance work, both on the monitoring equipment and on the control structures. The check dams in particular require sediment cleanout at least once per year on freshly reclaimed areas and less once vegetation is established, documenting their effectiveness but involving time and expense.

3.9.3.3 Monitoring and Reporting

The company proposed that the criteria for allowable change in in-stream TSS be based on a statistical comparison of suspended-sediment concentration within the receiving stream upstream and downstream of the disturbed area. The samples will be collected as outlined in the monitoring program described below. These data (TSS) will be normalized by a standard logarithmic transformation. The maximum period of runoff record for which sediment data are available will then be selected for use in the analysis described below.

The monitoring program was designed to quantify the impact of mine-area drainage on receiving-stream water quality. Data are collected on the receiving stream upstream of the disturbed area confluence as well as on the drainage from the disturbed area. Data are collected on an undisturbed drainage which serves as a control watershed. Non-recording rain gages are located at each monitoring site, and meteorological data are obtained from the existing mine meteorological network which includes a tipping-bucket precipitation gage. Both temperature and precipitation are measured, and the runoff source is described as snowmelt, rain and snow, or rain. In addition, three weighing-bucket recording rain gauges were installed to collect areal storm-intensity data. All stream-gaging stations were designed to monitor up to the maximum flow depth resulting from the 10-year 24-hour rainfall-runoff hydrograph as calculated with the SCS runoff technique. Computed peak-flow rates were used to calculate peak-flow depths for the 10-year 24-hour event using the continuity equation and Manning's equation.

The monitoring equipment used includes water-level recorders attached to servo-manometer gages located at each streamflow monitoring site. No flumes or weirs were installed, necessitating that flow measurements be undertaken periodically to construct and maintain rating curves. A crest-stage gage has been installed at each station as a backup to the water-level recorder.

U.S. PS-69 pump samplers are used to gather discrete water samples throughout a runoff hydrograph (U.S. Geological Survey, 1977). These are large samplers designed for remote sampling on flashy, ephemeral streams. In this sampler, 72 one-liter sample bottles are located below an array of distribution hoses. Sampler operation is initiated by a micro-switch tripped by the bubble-gage manometer when a flow event begins. The sampler can be set to pump samples on a time basis and/or change in water-stage basis. When both are operated simultaneously samples can be collected on the short-duration rising limb of the hydrograph by the delta-stage function and on the long-duration recession limb of the hydrograph by the time function. Thus, the entire hydrograph is adequately sampled. Samples can be collected every 15 minutes and with each 0.5-foot change in stage. Each time a sample is collected a mark is placed on the water-level recorder chart to record the exact time of sampling.

Sampler intakes float in order to allow sampling of stages from approximately 0.5 feet to the 10-year 24-hour flow depth. By using a floating intake, hydrograph-wide data are gathered on the suspended load transport which are comparable between stations. The intake is positioned perpendicular to the direction of flow and attached to a redwood float which keeps it off the bed and below water surface. As a backup to the pump sampler, one battery of U.S. U-59C single-stage sediment samplers is installed at each site. Data from the single-stage samplers will be used only in the event of a pump sampler failure. Calibration will be attempted using pump-sampler data and data collected with the use of a hand-held depth-integrated (DH-48) sampler.

Data collection is standardized. Log books containing data collection forms are maintained at each station. These forms are completed as a normal part of the servicing procedures. Field personnel are equipped with adequate tools and training to perform all routine data collection and maintenance functions.

Monitoring is conducted during runoff events between May 1 and October 31. When temperatures drop below freezing the PS-69 sampler pump castings may be broken by freezing water. Therefore, recorders and samplers are decommissioned for the winter. It can be assumed that the majority of data will be collected between the months of May and July.

If runoff is observed between November and April, grab samples are collected along with staff-gage measurements. Attempts are made to visit recording stations when precipitation is noted and runoff is likely.

Each monitoring station is serviced after each storm and once each month from May through October. In addition, checks are performed every two weeks from May through October to check battery voltage and pump-sampler and bubble-gage operation. After the first year of operation the frequency of these checks may be reduced depending on the observed reliability of the equipment.

Methods for data analysis include preliminary rating curves and tables developed using calculated discharge data. Measured stream cross sections and channel roughness coefficients were input to the HEC-2 backwater-curve computer program (U.S. Army Corps of Engineers, 1982). The resulting calculated water-surface elevation and specified stream-discharge data were plotted on log-log paper to produce a theoretical rating curve for each station. Low-flow discharge data are collected by field measurements to refine the theoretical curves. Discharge measurements are collected whenever possible, given safety restrictions. Indirect discharge-measurement methods such as the slope-area method are utilized to estimate peak discharges. Data reduction procedures are as described by Porterfield (1972).

After the data are reduced, they are analyzed statistically. Contingent on the dependency of sediment concentration on water discharge, either an analysis of covariance or an analysis of variance is performed as follows:

a. A linear regression of log sediment concentration (dependent variable) on log discharge (independent variable) is performed on the upstream and the downstream data.

b. Each linear regression is tested for the appropriateness of the regression. If either the upstream or downstream regressions are not statistically significant, the covariance analysis cannot be used and the analysis of variance procedure must be used as described in step e below.

c. If the regressions are valid, then the slopes of the regression lines are tested for parallelism. If they are not parallel, then covariance cannot be used and the analysis of variance procedure is used. If the slopes are parallel, the covariance analysis proceeds.

d. The regressions are tested for intercept. If the upstream regression has an intercept statistically greater than or equal to the downstream regression, then no degradation occurred. This concludes the analysis of covariance.

e. If the analysis of variance is used, then the suspended-sediment concentration data for the upstream and downstream data sets are compared for similarity. If the upstream population mean is equal to or greater than the downstream population mean, then no degradation has occurred.

The company is required to report monitoring results to the regulatory authority on a quarterly basis. Individual storm-water samples and data must be processed within eleven days of storm occurrence. If degradation is detected during the data analysis, both the state regulatory authority and the OSM must be notified within twelve days of storm occurrence, otherwise the results will be forwarded to the state regulatory authority quarterly as noted. Within one day of data collection the state regulatory authority is notified that samples have been collected and sample processing and data analysis have begun.

Regulatory compliance is based primarily on the construction and diligent maintenance of the control structures and the data from the monitoring stations. Because of the changing nature of the mine, it is necessary to update on an annual basis the map that shows needs for alternative sediment-control techniques during the upcoming year.

In the event that runoff data should show degradation of receiving-water quality during a runoff event, the alternate sediment-control program will temporarily be out of compliance. The possibility of temporary non-compliance also exists for a sediment-pond control program where dams can wash out or settled sediment can be resuspended during discharge. The immediate concern of the company will be to identify the problem areas and take corrective measures to comply with regulatory obligations. The company, in the permit application, noted that the alternate sediment-control techniques described above have been historically successfully implemented in agriculture and highway construction. Alternate sediment control is proven technology in other industries and should be considered workable in the surface coal mining industry. No new or untried technology is proposed.

3.9.3.4 Evaluation Criteria

Two types of evaluation criteria must be examined for this case study. Evaluation of the alternative sediment-control program itself, i.e., determination of receiving stream degradation, is described in the previous section. It is also interesting to examine the evaluation criteria used by the regulatory authorities to approve the program.

The State Decision Document included a determination as to whether the alternative sediment-control practices will comply with established procedures for variances. In this particular case the issue was whether the proposed alternative sediment-control plan would protect receiving-water quality and encourage advances in mining and reclamation technology. The following findings, taken directly from the state decision document, indicate that the state does feel that this plan would comply with this variance requirement.

> In the review of applicable Federal and State regulations, it is evident that the use of sediment ponds are considered to be the best technology currently available to control sedimentation and protect receiving water quality. The coal mining industry as well as professional hydrologists and geomorphologists are often of the opinion that although sediment ponds may very well be the best technology currently available to

protect perennial stream water quality in the eastern United States, they are not the best, or most practical technology currently available to protect ephemeral stream water quality in semi-arid regions of the western United States.

The potential benefits of using alternate sediment control techniques instead of sediment ponds to protect the quality of receiving streams are as follows:

1. The lack of sediment ponds will lead to less land and wildlife habitat disturbance.
2. Alternate sediment control techniques will keep topsoil and subsoil on site where it is most useful for revegetation efforts.
3. Several alternate sediment control techniques result in less runoff which may lead to greater soil moisture, providing for more successful revegetation.
4. Alternate sediment control techniques may be more cost effective than sediment ponds.
5. The consequences of sediment pond dam failure and associated environmental degradation are eliminated.
6. Channel incision below sediment ponds, resulting from TSS concentrations well below ambient conditions, is eliminated.
7. Alternate sediment control techniques minimize the retention of runoff from undisturbed areas thereby providing more water to downstream water users.

To date little, if any, meaningful suspended sediment data has been collected in areas being affected by coal mining activities in semi-arid areas of the western United States. Therefore, this experimental practice will not only determine the adequacy of the alternate sediment control techniques proposed but will also adequately quantify ambient water quality conditions and streamflow conditions in ephemeral streams. This information, coupled with precipitation data, will greatly further the understanding of ambient and mining disturbed runoff conditions. In turn this can be used to adjust analytic techniques used by the mining industry and regulatory authorities in the development of mine drainage plans etc.

Additionally, data collected as a result of this proposal will also be able to be used for the development and calibration of various hydrologic and sedimentation models, such as the SEDIMOT II model which is currently receiving much attention from the coal mining industry as well as the Office of Surface Mining and other regulatory agencies.

The OSM, in their analysis of the experimental practice request dated July 15, 1983, reviewed the proposal for compliance with criteria outlined in January 16, 1983 procedures issued by the Assistant Director for Technical Services and Research. These criteria and OSM's findings are shown below. The first three criteria are taken directly from SMCRA (Section 711).

Criterion 1:

The experimental practice is potentially more, or at least as, environmentally protective during and after mining operations as those otherwise required by Title 30 Chapter VII of the Code of Federal Regulations, and the experimental practice proposal is technically sound.

These issues are discussed in the justification Section of the company proposal and include consideration of sediment control.

The various structures and vegetative measures to be placed on the permit area will afford suitable sediment control as expressed by the SEDIMOT II hydrology and sedimentology model, and industry standard. Also, the company has designed a monitoring and data-analysis system that will identify receiving stream degradation, should it occur. In addition, the company has committed to diligent corrective measures; and, ultimately the construction of sediment ponds if the alternate control practices do not produce the results anticipated.

Criterion 2:

The operations involved are not of a larger scope or more numerous than necessary to determine the effectiveness and economic feasibility of the experimental practice.

As previously described, the existing total disturbed area on the mine is 3,580 acres. The company proposes to control runoff and sediment from 612 acres using alternate control practices; and 2,968 acres will be controlled by sediment ponds and drainage to the pit, where water is collected in holding ponds and treated before release to area streams.

The alternate practices will be applied to three tributary watersheds on enough area in each to determine the full effect of the practices on the hydrologic balance of those watersheds. The proposal is, therefore, of sufficient scope to determine effectiveness and economics of the practices, but is not larger than necessary to determine effectiveness.

Criterion 3:

The experimental practice will not reduce the protection afforded public health and safety below that otherwise provided by Title 30, Chapter VII of the Code of Federal Regulations.

The experimental practice poses no hazard to public health and safety. With the monitoring equipment to determine sediment load and the designed system in place, the likelihood of excessive silt loads or damaging drainage runoff is minimal. The alternate sediment control structures will be inspected monthly and after each rainstorm. Repairs will be made as soon as equipment can safely and effectively operate. In addition, the company has agreed to construct sedimentation ponds in the event the system does not provide proper environmental protection.

Criterion 4:

The duration of the experimental practice is reasonable and the extent and duration of the operators' self-monitoring and reporting program is adequate.

OSM, as well as the State of Wyoming, adds the following stipulation to clarify that the duration of the practice is the applicant's term of permit which has about 4½ years remaining. Approval of this experimental practice variance is authorized for the remainder of this permit term or until monitoring data indicates compliance problems, whichever comes first. Continued authorizations of the variance shall require review at each renewal, with the results showing satisfactory performance of the system.

The proposed monitoring program will quantify the impact of mine area drainage on receiving stream water quality. Data will be collected on the receiving stream upstream of the disturbed area confluence as well as on the drainage from the disturbed area. Data will be collected on an undisturbed drainage to serve as a controlled watershed. Clear-Vu storage rain gages will be located at each monitoring site and meteorological data will be utilized from the existing mine meteorological network. Both temperature and precipitation will be noted, and the runoff source will be described as snowmelt, rain and snow, or rain. In addition, two weighing bucket recording rain gages will be installed to collect areal storm intensity data. All stream gaging stations will be designed to monitor up to the maximum 10-year 24-hour runoff depth resulting from 10-year 24-hour rainfall runoff hydrograph as calculated with the SCS runoff technique.

In addition, the company will send monitoring results indicating degradation of total suspended sediment concentration of the receiving stream, if this should occur, to DEQ, OSM/WTC, and OSM/Casper immediately after the analyses are obtained.

A copy of each of the planned quarterly reports that include information on the application of the experimental practice, monitoring results, interpretation of results with respect to protection of the hydrologic balance, problems encountered, mitigation of problems, and plans for the next quarter will be sent to OSM/WTC as soon as practicable after each quarterly period.

OSM's analysis report contains the following recommendations:

> Based on the preceding analysis and the findings of the Wyoming Department of Environmental Quality (Attachment A) the WTC recommends that the experimental practice request be approved with indicated stipulations. The company has done an outstanding job of consulting regulatory agencies throughout the planning of this project to produce a proposal with excellent chances for success. The proposal presents the opportunity to effectively control sediment while simultaneously reducing reclamation costs.
>
> [The] Company should be commended for their efforts and cited as an example of how innovative reclamation can benefit environmental resources and the coal operator.

3.9.4 Identification of Issues

The alternative sediment-control program described above was approved for one permit term. It is subject to revocation if water quality degradation (TSS concentrations) in the designated receiving stream is detected. Degradation is defined as a statistically significant increase in TSS concentrations below the disturbed area. Recognizing that the regulatory authorities need some way to quantitatively evaluate the proposal, it is still interesting to note that the regulatory approval could be revoked if receiving stream TSS concentrations increased slightly above the calculated ambient level (estimated at 30,000 mg/l) for this particular stream.

It is not clear from reading the OSM and State Decision Documents exactly how the sediment-control practice will be evaluated. As stated in Section 3.9.1, the OSM seems to infer that evaluation will be based on a comparison with point-source effluent standards, considered best practicable technology (BPT). The plan does not attempt to achieve these effluent standards, basing evaluation of success on non-degradation of receiving-water quality, a concept apparently also put forth in the State Decision Document.

The wide discrepancy between effluent quality from the alternative sediment-control program and effluent quality from a conventional sediment pond (35 to 70 mg/l) is possible only because the alternative sediment control program is considered a non-point source and as such is not subject to point-source effluent limitations. There are no regulations or standards that tell how to distinguish between check dams, toe ditches, or other small control structures and conventional sediment ponds so as to determine which is a point source and which is a non-point source. The arguments in favor of the alternative sediment control contained in the company's proposal and in the regulatory authorities' decision documents seem to emphasize the advantages of alternative forms of sediment control over sediment ponds where the receiving streams are ephemeral (and therefore naturally high in TSS concentrations). It is ironic that a discharge from a sediment pond containing water with a TSS concentration of 71 mg/l (one mg/l in excess of the point-source effluent standard) could result in a notice of violation being issued to the operator, while a discharge from a rock check dam can have a TSS concentration measured in the tens of thousands and remain fully in compliance with all statutes and regulations and have no adverse impact on water quality.

The states are expected to revise their effluent standards to comply with the revised Federal point-source standard, which is 0.5 mg/l of settleable solids rather than a TSS standard. This may help to resolve this inequity, but will need to be specifically addressed in revised design and performance standards.

The mine in this case study may benefit substantially from alternative sediment control due to its particular situation. The high drainage density of the permit area would have required construction of over 200 conventional sediment ponds. Not all mines are faced with this situation and for other mines the monitoring, reporting and inspection requirements that accompany this alternative sediment control program may outweigh any economic benefits of alternative sediment control.

Another issue illustrated by this case study is the high quality of data-collection and evaluation techniques that are achieved when the monitoring program is designed to provide specific criteria for the evaluation of success of a particular practice.

3.10 Case Study J

3.10.1 Focus

This case study examines a mine that contains an alluvial valley floor (AVF) that was determined not significant to farming. The purpose of this case study is to illustrate the methods used to identify an area as an AVF, to determine its essential hydrologic functions and significance to farming, and to restore the essential hydrologic functions during reclamation.

3.10.2 Description of Mine and Hydrologic Setting

The study mine is a strip coal mine located in Campbell County, Wyoming. The mine began operation in 1982 and will have a 44-year life.

Coal production from the subbituminous Roland seam will be 5 million tons per year.

The study mine is situated on the east flank of the Powder River Basin. The mine area is characterized by a radial drainage pattern with several deeply incised ephemeral streams draining into an intermittent stream which runs through the center of the permit area. The deeply incised channels and heavy erosion in the area indicate that the location is subject to sudden and turbulent surface-water flow.

An alluvial valley floor not significant to farming was declared to exist within the permit area. The majority of the AVF acreage lies adjacent to the intermittent stream within the main body of the permit area, with minor AVF acreages present along small ephemeral tributary channels.

3.10.3 Presentation of Case Study

3.10.3.1 Baseline Data

The data used to identify the presence and extent of the alluvial valley floor (AVF) include aerial photography, study of topographic maps, surveying and drilling of alluvial wells and digging backhoe pits to physically inspect the soil strata and the relationships between the root zone and the shallow aquifer. The surficial geology was initially identified through the study of aerial photographs and topographic maps. This initial investigation was then followed by intensive field inspection and surveying. Auger holes were drilled and backhoe pits dug to obtain the information necessary to construct alluvial cross sections. The resulting surficial geologic map and alluvial cross sections were used to identify the extent and depth of alluvial deposits along streams. Nine alluvial cross sections were developed at the study mine based on fifty-three alluvial wells and eleven backhoe pits.

The presence of subirrigated and naturally flood irrigated plant species on the unconsolidated streamlaid deposits was initially assessed through the use of infrared aerial photography. The areas containing subirrigated or naturally flood irrigated plant species as identified on the aerial photographs were then subjected to intensive field studies. Subirrigated areas were found to cover about ten percent of the unconsolidated stream laid deposits.

Based on the above data used to make the initial identification of the AVF acreage and on subsequent field investigation by personnel of the regulatory authority, the regulatory authority declared the existence of an AVF within and adjacent to the permit area.

Artificial, or man-made, flood irrigation that is occurring at the study mine was identified in two steps. First, a complete review of existing water rights and their respective uses within the mine-permit area and on adjacent land was undertaken. The findings of this review were then corroborated by intensive field investigation. This field work essentially consisted of walking along the stream channels to make an inventory of any artificial structure used to enhance or develop flood irrigation, e.g. spreader dikes or diversion structures. This investigation indicated that artificial flood irrigation is not currently practiced within the mine-permit area except for a small portion of a hay field; the majority of the hay field is outside of the permit area. The small portion of the hay field that is within the permit boundary will not be affected by the mining operation. With the exception of the small area of existing flood irrigation, the entire permit area is used as range land. Therefore, the declared AVF was declared not significant to farming, and mining was not prohibited.

Areas within the permit boundary that have the potential for artificial flood irrigation were also identified. This potential was based on four considerations: (1) soil quality, (2) water quantity and quality, (3) topography and (4) degree of success of previous attempts at artificial flood irrigation in the area.

Water quality data used to determine the suitability of surface water for flood irrigation was determined through a monitoring program. This program consisted of streamflow quantity and quality monitoring at six locations, including two locations on the main intermittent stream (above and below the permit area) and one location on each of four small ephemeral tributary channels. The ephemeral channel monitoring sites were located so as to include areas within and adjacent to the mine-permit area. The surface-water quality monitoring program consisted of collecting samples from single-stage sediment samplers at five of the above six sampling locations and grab samples from all six sites when flowing water was present. The surface-water samples were analyzed for a wide range of parameters, and the results indicated that the surface-water quality is dependent upon flow conditions. Hardness, dissolved solids and sulfate concentrations were reduced during periods of high flow whereas iron, nutrients (nitrogen and phosphorus) and suspended solids increased in concentration during periods of high flow. The results of this monitoring program indicated that the surface water is of acceptable quality for flood-irrigation purposes.

Surface-water flow was monitored at the same six locations used to monitor water quality. The streamflow monitoring system consists of water-level recorders and crest-stage gages on the main intermittent channel above and below the permit boundary and on three of the four ephemeral tributary channels. A pair of crest-stage gages is located on the fourth ephemeral channel. The data collected from these flow monitoring sites and the topographic characteristics determined from on-site investigations indicate that water supply and topographic features conducive to artificial flood irrigation exist on one of the ephemeral channels and on the intermittent channel. The other ephemeral tributaries have an inadequate water supply and/or topographic constraints (incised nature of the draws or rugged topography adjacent to the tributaries).

The soil characteristics of the two areas shown to have favorable topographic features and sufficient water supply were then investigated to further determine their potential for artificial flood irrigation. A soil sampling and testing program was used to determine if the soil quality is acceptable for flood irrigation. The tests indicated an overall poor quality of soil with no lands being classified as Prime Farmlands as determined by the U.S. Soil Conservation Service. No acreage adjacent to the ephemeral tributary channel was determined to be suitable for flood irrigation. However, over 100 acres of land adjacent to the intermittent stream have suitable soil quality, water quality and quantity, and topography to be potentially flood irrigable.

The potential to develop flood irrigation was further defined by a thorough review of previous attempts at artificial flood irrigation. At the study mine, this investigation revealed an attempt to develop flood irrigation by constructing a spreader dike on the intermittent channel. This effort failed due to the unsuitability of the site selected and the instability of the valley fill used to construct the dike. The water did not spread out on adjacent lands as intended, but rather incised a new channel around the diversion dike and back into the stream. The propensity of the creek to exhibit "flashy" type floods with high discharges and short durations contributed to the unsuitability of a water-spreader irrigation system. Artificial flood irrigation was also limited by poor topsoil quality in the area to be mined.

3.10.3.2 Analytical Techniques

Groundwater drawdowns in the intermittent creek alluvium were estimated using a wellfield simulation. This technique involved the theoretical placement of wells at locations in the mined area corresponding to various stages of mining. The simulated wells are pumped to calculate drawdown and recovery rates. Results of this wellfield simulation, which involved manual calculations as opposed to a computer model, for the alluvium indicated that any moderately-sized flood-runoff event would totally recharge the dewatered alluvial material. This procedure led to the conclusion that surface-water runoff, not drawdown around the pit, will determine water levels, amount of drawdown, and rate of water-level recovery in the alluvium.

The study mine has made a commitment to employ special measures to facilitate subirrigation along the reclaimed portion of the intermittent stream that transects the mine-permit area. This commitment includes the separate salvage and stockpiling of all coarse-textured alluvial deposits found along the intermittent stream.

This alluvial material will then be "replaced in the reconstructed channel so as to be in hydrologic communication with the active channel to facilitate subirrigation." Although prior to mining subirrigation was evident within the confines of the active channel, postmining reclamation will attempt to promote subirrigation not only within the active channel but also within an 80-foot wide reclaimed low flow channel.

Prior to mining, the AVF area was a local discharge area for the coal and overburden aquifers. This discharge from the bedrock aquifers helped to maintain the groundwater levels in the valley floor and thereby helped support subirrigation. Following mining the water levels in the spoil are expected to return to premining levels, and the restored valley is expected to become a discharge area, similar to premining conditions. Recognizing that it may be many years before this occurs, the operator is placing a compacted clay soil layer beneath the restored alluvial aquifer. Until the spoils in the area resaturate, this will hydraulically isolate the restored alluvial system from the remainder of the spoils. As streamflows occur in the restored channel and recharge the replaced alluvial aquifer, this clay layer will "perch" the alluvial water above the dry spoils, helping to shorten the time for subirrigation to resume.

Subirrigation and hydrologic communication between the reconstructed and undisturbed portions of the intermittent stream will be promoted by placing a 10-foot thick layer of coarser-grained alluvial material beneath two feet of suitable topsoil and above 10 feet of suitable overburden and the compacted clay soil layer in the 80-foot wide reconstructed low-flow channel. The extent and texture of these coarser-grained alluvial materials were determined by the premining backhoe-pit analyses, alluvial well logs, and field inspection. These evaluations indicated that an adequate volume of suitable alluvial material is available with which to restore the hydrologic functions of the alluvial aquifer.

Separate overburden stockpiles have been established for suitable alluvial material in order that a sufficient amount will be available for channel reconstruction. The premining investigation indicated that approximately 16 times the required amount of alluvium needed for alluvial aquifer reconstruction will be available. During reclamation operations, the coarser-grained alluvial deposits suitable for channel reconstruction will be identified by field inspection. The study mine has committed to contact the regulatory authority so that it can be documented that adequate and appropriate-textured materials are being salvaged.

3.10.3.3 Monitoring and Reporting

Monitoring of the restored AVF will include:

1. Streamflow quality and quantity monitoring to partially define the postmining potential for flood irrigation;
2. Continuous recorders on alluvial monitor wells to record seasonal and diurnal water-level fluctuations in the restored alluvial aquifer to help quantify water used for subirrigation and as an aid in determining impacts to subirrigated areas;
3. Sampling to determine alluvial water quality; and
4. Pump tests to determine aquifer characteristics.

Three groups of alluvial wells were installed in transects to monitor the potential extent of material damage to the alluvial valley floor downstream from the mining area. One group of alluvial monitor wells was located on sections of the valley alluvium which will not be mined, enabling continuous monitoring throughout the mining and reclamation operations.

The surface-water monitoring results will be supplied to the regulatory authority in quarterly reports. Monitoring of the alluvial wells for water levels and for groundwater quality will also be on a quarterly basis. Any exceedence of water-quality standards will be reported immediately to the regulatory authority.

3.10.3.4 Evaluation Criteria

The premining monitoring and data-collection program at the study mine was established in part to define the existence and extent of an alluvial valley floor. The goals of this program were to:

1. Define the presence, areal extent, and depth of unconsolidated streamlaid deposits;
2. Define the existence, extent, and source of water for subirrigation;
3. Define baseline alluvial water quality;
4. Define the extent of existing flood irrigation and areas of potential flood irrigation; and
5. Define topographic and soil conditions suitable for subirrigation or flood irrigation.

A postmining spoil and reclaimed alluvium monitor-well system was designed to:

1. Determine the characteristics of the spoil and reclaimed alluvial aquifer;
2. Determine impacts of the mining operation; and
3. Satisfy state and federal regulatory requirements relevant to groundwater monitoring.

The information available through this monitoring program will allow for a comparison of the pre- and postmining conditions. This will in turn provide criteria to evaluate the success of the reclamation program.

Reclamation of the alluvial valley floor within the permit area will be evaluated with respect to restoration of the hydrologic functions of the alluvium. Postmining subirrigation will be demonstrated by the extent and variation of plant species that are established on the reclaimed alluvium. The effect that mining has on the water levels in the alluvium will be demonstrated by the alluvial wells that have been established in areas that will not be disturbed during mining. The water-level data will reveal any changes between the premining and postmining alluvial water levels. This program will determine if water levels recover to a depth sufficient to maintain subirrigation on the valley floor in an area not less than was subirrigated under premining conditions.

3.10.4 Identification of Issues

This case study discusses the identification of an alluvial valley floor, definition of its significance to farming, and special handling techniques used to reclaim the AVF in order to restore essential hydrologic functions. The identification of an area as an AVF essentially involved a two-step process: (1) preliminary investigation to roughly define areas of subirrigation or natural flood irrigation using aerial photography and topographic maps, and (2) field inspection to specifically identify alluvial material and to define the alluvial characteristics using backhoe pits and alluvial wells. This process allows for accurate delineation of the extent and depth of the AVF and determination of its essential hydrologic functions.

The special techniques for the restoration of the AVF included separate stockpiling and replacement of alluvial material in a geometric configuration that, coupled with the geometry of the restored channel, should restore the premining function of the alluvial aquifer. The placement of a compacted clay soil layer beneath the restored alluvium will hydraulically isolate the alluvial system from the remainder of the spoils. This will reduce the time required to evaluate the success of the alluvial reclamation plan and will allow for the rapid resumption of subirrigation.

This case study once again illustrates that data-collection and analysis are best done when there are specific goals in mind. AVF identification and restoration requirements require specific and detailed baseline investigations, which in turn provide specific criteria for the design and evaluation of the reclamation plan.

Even with the special measures that will be implemented in the restoration of the AVF, the application alludes to uncertainties as to the time that will be required for restoration of the EHF, particularly subirrigation. In spite of special measures to hasten the restoration of subirrigation, the EHF may not be fully restored within the bond-evaluation period.

3.11 Case Study K

3.11.1 Focus

This case study was intended to examine an innovative method of surface-water restoration. At the time that research for this case study was performed (January 28, 1985), the approved permit document contained a unique plan for channel restoration. Since that time, the company has submitted a revised permit application, and the method for channel restoration has been revised. However, a discussion was retained in this document to point out some interesting aspects of evaluation of reclamation.

3.11.2 Description of the Mine and Hydrologic Setting

This mine is a dragline surface coal mine located in southern Wyoming. Operations commenced in 1972, and mining is projected to continue through 1990. The permit area covers about 7,400 acres, of which about 2,200 acres will be disturbed.

The mine is in a plains area where peak flows occur primarily from rainstorm runoff. All drainages within the area to be affected are ephemeral.

The mine has been classified as a thick-overburden mine. Mines in this area generally have excess spoils averaging about 10 percent. In other words, the volume of the disturbed spoil, considering the swell factor, is about 10 percent greater than the combined volume of the undisturbed overburden and coal. In "grandfathered" areas, long spoil ridges with maximum slopes ranging from 3H:1V (three horizontal to one vertical) to 5H:1V remain. Areas that have been or will be reclaimed since 1977 have slopes ranging from 4H:1V to 8H:1V. Due to the excess spoil, topographic relief after mining will be about 10 percent greater than premining relief. To compensate for the increased erosion that might result from the increased relief, the operator's permit document cites measures that are being taken to adjust other drainage basin variables. It is stated that infiltration will be increased, hence runoff decreased, by replacing bedrock of low infiltration capacity with spoils of higher infiltration capacity. Channel gradients will be similar to or flatter than premining gradients, and reconstructed channels will be revegetated in order to, "...increase their roughness coefficient and decrease erosive velocities...".

Mean annual precipitation in the area is about 10 inches. The majority of the annual runoff occurs during the months of February through May. Most annual peak flows occur during the summer months of June, July and August in response to localized thunderstorms.

The general drainage pattern is a coarse-textured, dendritic pattern. In localized areas the presence of a trellis and parallel subdrainage pattern indicates control by the steeply-dipping, folded sedimentary rocks.

The applicant, in the permit approved in June 1982, describes how the use of sediment ponds and "other sediment control techniques" should adequately reduce the potential for increased sedimentation due to mining activity. Contour berms and retention ditches were proposed and implemented, as alternate sediment control measures, to intercept surface runoff and trap sediment from disturbed areas. It is not explained in the State or Federal decision document why these alternative sediment control measures were approved as written, considering that the mine in the case study of Section 3.9 was required to go through a rigorous design and monitoring program in order to get a similar alternative sediment control plan approved or approval to use a small area as an experimental practice.

Of primary interest to this case study is the operator's plan for surface-water restoration in this area of steep slopes. In response to a stated regulatory-authority concern, the operator took measures to avoid creation of drainage basins consisting of long, parallel spoil ridges with the drainage paths running longitudinally between them. To avoid this situation, the operator's plans call for replacement of drainage channels in approximately their original locations. To do this, the spoil ridges are regraded in some areas to eliminate long, straight drainage channels.

The operator stated that reconstruction of drainage channels in their original locations, "...forces the reestablishment of the original channel slopes...". It was further stated that, "No attempt will be made to reconstruct channels having a specific cross section or design. The areas where the drainage channels will be allowed to form will be graded smooth and relatively flat, with a maximum longitudinal slope of 2 percent. The channels will then form on their own through the scouring and depositing of the fill material."

As previously stated, the operator submitted a revised permit application to the regulatory agency on about February 1, 1985. The revised application now states that the operator will provide hydraulic designs for reclaimed channels. These designs will include a V-shaped guide channel sized to convey the 2-year 24-hour peak discharge and a flood plain designed to convey the 100-year flood. The design velocity will be 4.5 feet per second (fps) or less, and the assumed roughness coefficient (Manning's n) will be 0.035. The reason for this change is that the regulatory authorities inspected the mine in the summer of 1984, saw that erosion was occurring, and decided not to allow the previously requested type of reclamation (based on a personal communication with the mine hydrologist on March 7, 1985).

3.11.3 Presentation of the Case Study

3.11.3.1 Baseline Data

Surface-water data presented in the application are sparse. Seven surface-water sampling sites are located within the mining area. Of these, three are point-source discharges from existing sediment ponds. The remaining four sites are on streams within the mine area, none of which will be disturbed by mining. These monitoring sites consist of crest-stage gages with single-stage sediment samplers. The operator has committed to collecting grab samples at these sites for water quality analysis "when possible." A search of the records of the State Engineer's Office, conducted during the permit application process, showed there are eight existing surface-water rights on affected drainages, all of which are mine sediment ponds belonging to this operator or adjacent mines.

The State regulatory authority, in its decision document for this mine, stated that the surface-water monitoring plan "...appears to be satisfactory." However, "...past performance in this area has been inadequate, resulting in an almost total lack of baseline data. Only three surface-water samples have been collected thus far from the seven existing sites."

OSM, in their oversight reviews, stated concerns over the lack of surface-water monitoring data collected by the operator. In response, the State regulatory authority stated that data from other mines in the vicinity and USGS sampling stations downstream were found to be sufficient to characterize baseline surface-water quality for the permit area.

Regarding the operator's plans to let restored channels form, "...on their own through the scouring and depositing of the fill material...", the operator pointed to another channel in the permit area that was a, "... good example of this reconstruction technique." This was a channel that had been regraded two years earlier, and specific drainage channels had been allowed to form on their own through the scour and deposition process described above.

3.11.3.2 Analytical Techniques

The analytical technique utilized in this case is not based on any conventional mathematical or modeling approach. However, the channel-forming process is reasonably well understood and has been the subject of numerous text books, professional papers, and laboratory research projects. Though not specifically analyzed, it is based on the knowledge that flowing water can sort its bed material and shape its channel as a function of flow depth and velocity and the particle-size gradation of the channel bed.

3.11.3.3 Monitoring and Reporting

There are no monitoring and reporting requirements specifically related to the channel-restoration method that is the focus of this case study.

3.11.3.4 Evaluation Criteria

A problem with this approach to channel restoration is that no specific evaluation criteria were established. While it was stated that the channels would be allowed to form on their own through scour and deposition, no parameters were established with which to measure the rate at which these processes were occurring and to determine whether this rate was acceptable. Depth of scour was not measured following runoff events, and no attempt was made to model the erosion rate and thereby make predictions as to the ultimately-resulting channel and flood-plain geometry and project when and if equilibrium would be reached between erosional and depositional processes. No criteria were established to distinguish between incipient stages of channel formation and erosional rills. Also, no TSS measurements were made above and below the formative channels to determine whether water quality impacts during channel formation were within reasonable limits.

3.11.4 Identification of Issues

Because of the lack of established evaluation criteria, it is understandable that when the regulatory inspections were made during the summer of 1984 and channel erosion was noted, there was concern regarding channel stability and water-quality impacts. Had these been designed channels, such erosion might have indicated under-design.

However, in this case, channel erosion was to be expected by the definition of the restoration technique. Therefore, if specific criteria had been established, the extent of erosion could have been evaluated with respect to the magnitude of the flow event that occurred and the resulting water quality, and objective decisions could have been made regarding the suitability of this restoration technique.

The operator has noted (personal communication, March 7, 1985) that under the revised submittal, he is under no obligation to replace channels already restored in this manner with specifically designed and constructed channels. However, no evaluation criteria and no specific monitoring plans were developed for these "completed" channels. Depending upon the runoff events that occur in these channels prior to bond release, the regulatory agency could require the operator to perform remedial measures at each point where erosion occurs. Since erosion must occur for this channel restoration technique to succeed, reclamation will never be completed if the operator has to make "repairs" each time a runoff event occurs.

Even if these channels do not show evidence of erosion during the bond evaluation period, there may be stability problems. This is a potential problem even for designed ephemeral channels. Most permanent channels are designed for 100-year flood flows, and in many cases a guide channel is provided to carry a higher-frequency peak flow, such as the 2-year or 5-year flood (see Section 2.3.2.4). Considering that a bond-evaluation period on a given reclaimed area is about 10 years, there is a good chance that flows of sufficient magnitude to provide a true test of channel and flood-plain stability will not occur during the bond-evaluation period. Since stability of the entire spoil surface depends heavily on stability under the effects of water erosion, there is a need to develop quantitative evaluation criteria for restored ephemeral channels.

One other issue that exists is the implication by the operator that restoration of premining channel gradients will provide channel stability. While this may generally be the case, the application also states that in some areas the drainage pattern is a trellis type, indicating the influence of bedrock on the development of the drainage system. If premining channel slopes are maintained by relatively resistant bedrock, it may not be correct to assume that a channel constructed in spoil material at the premining slope will be stable (see Section 2.3.2.4).

The amount of baseline data required of this applicant is much less than that described in other case studies, such as those described in Sections 3.5 through 3.10.

The applicant openly proposes, and apparently implements, an alternative sediment-control program similar to the one described in Section 3.9. It is not clear why the regulatory authorities did not require an experimental practice procedure and corresponding monitoring and evaluation program similar to that described for Case Study I.

These latter two issues seem to indicate inconsistencies in the administration of the regulatory program.

3.12 Case Study L

3.12.1 Focus

The focus of this case study is primarily to summarize the sources of data and methods of analyses used by the applicant to predict groundwater impacts from mining and the time required for reestablishment of the water table in the backfill. Federal regulations state that the regulatory authority will perform the cumulative hydrologic impact assessment (CHIA) due to mining operations. However, in this case the mining company has undertaken the task by using the Prickett-Lonnquist model, a digital computer model, to determine the extent of drawdowns from pit-dewatering operations for all mines in the general groundwater area. The application of this model is described in Section 3.12.3.2.

3.12.2 Description of Mine and Hydrologic Setting

This mine is an open-pit surface coal mine extracting State and Federally-owned coal. Mining began in 1978. The coal seam is nearly level and the surface terrain is also nearly level to gently rolling. Some isolated areas of the coal seam dip steeply. Overburden is thin compared to the thickness of the coal. Electric shovels are used to excavate the overburden and coal and materials are hauled by diesel-electric and mechanical drive end-dump trucks. Current production is approximately 12 million tons per year, with an ultimate production rate of about 26 million tons per year.

The mine is located on the northeastern edge of the Powder River Basin. The coal and overburden in the area dip generally less than five degrees to the southwest. The coal being mined is the Wyodak seam which is generally considered the upper contact of the Fort Union Formation. The overburden bedrock material is made up of the Wasatch Formation. The average thickness of the Wyodak seam at the mine is 112 feet, but thicknesses range from nearly 200 feet to zero feet at the cropline. A consistent carbonaceous shale parting exists in the Wyodak coal within the permit area.

Five aquifers have been identified at the mine. These include the Wyodak coal seam, sandstone lenses in the Wasatch Formation, scoria bodies, a channel which cuts through the coal seam, and the alluvial aquifer of an intermittent stream which passes through the permit area.

A prominent hydrogeologic feature influencing the intermittent stream is the channel of no coal deposition or post-depositional erosion called the no-coal channel. In place of coal, low-permeable claystones and shales were deposited in this area. The low-permeable materials in the no-coal channel act as a natural barrier to regional groundwater flow, forcing some groundwater into the alluvium and channel of the intermittent stream valley.

Although scoria areas within the permit area are highly porous and permeable, they are less important features of local hydrology because of their isolated nature. The most significant scoria body in the permit area is in direct communication with the coal. Recharge to the coal from the scoria is limited only by the low permeability of the coal. Other scoria bodies occur in the area of the no-coal channel, and while they may store water from surface infiltration, they are perched on shales and are not in hydraulic communication with the coal.

Overburden sandstones within the Wasatch Formation are the most influential groundwater aquifer in the permit area. They provide the most extensive recharge areas for the coal and discharge significant amounts of water to the intermittent stream. They are largely responsible for sustaining subirrigation in the valley below the permit area.

Where the sands immediately overlie the coal, the coal and overburden water tables are unconfined and coincide. In other areas, the sands may be perched above a shale that overlies the coal. In some areas the sand is overlain by shale, in which case groundwater within the sand is confined.

Data from deeper water-supply wells drilled at the mine indicate that the Fort Union Formation remains rather impermeable to a depth several hundred feet below the coal. Relatively high-yielding wells may be developed in sands below this deeper zone. The sediments above these sands are predominantly fine-grained, low-permeable clastics characteristic of the fluvial deltaic depositional environment of the Fort Union Formation. Sands, where encountered, are typically fine-grained and presumably lenticular and discontinuous.

Alluvial deposits along the intermittent stream are thin deposits of predominantly silty and sandy clay. They are relatively impermeable and transmit very little water down the valley as underflow. Where the effects of groundwater are seen at the surface, i.e. subirrigation, it is primarily a result of direct communication with underlying bedrock aquifers. The application states that these deposits cannot properly be called an aquifer. No successful pump tests have been performed because of the low permeability of the sediments. Their primary function, where present, is to perch the stream and store infiltration of surface runoff.

It is interesting to note that radically different conclusions were drawn by another mining company in an AVF investigation of this same stream immediately downstream from the mine of this case study. In this lower reach several aquifer pumping tests were successfully conducted from which alluvial permeability values were determined.

3.12.3 Presentation of Case Study

3.12.3.1 Baseline Data

The mining company collected various hydrogeologic data to assess premining groundwater characteristics within and in the vicinity of the mine-permit area. The groundwater information developed is based on data and interpretation from over 50 groundwater wells. Some of the wells have been destroyed by mining; the remaining wells are located within and west of the permit area. Additional data were collected from adjacent operators' wells north and east of the permit area.

The monitoring wells maintained by the applicant are completed in the various aquifers. One well is in the scoria aquifer and is used to monitor water levels in the scoria, conduct pump tests, and collect water-quality samples. A two-week pump test conducted by the applicant in the scoria showed transmissivities to be extremely high.

Five monitoring wells have been placed in the overburden sandstone and no-coal channel areas. Seven wells are completed in the alluvium of the ephemeral stream.

The coal aquifer is monitored with observation wells located throughout the permit area. Other monitoring wells in the coal aquifer exist to the north and to the east at one existing and one proposed surface coal mine. These other coal companies monitor groundwater levels in wells located on their property. Two additional wells monitor water levels in aquifers beneath the coal.

Pump tests were conducted by the operator in the coal and overburden. Pump tests of overburden wells generally consisted of a "cluster" of three wells containing one pumped well and two observation wells. Observation wells were positioned 20 to 50 feet from the pumped well.

The coal seams store water, with flows occurring through fractures in the coal. Single-well slug tests and recovery tests by the applicant yielded a wide range in transmissivity values. Some of the test values may be somewhat low because the test data were affected by variability in coal-fracture densities and fracture orientations. The permit application also references other coal-aquifer test results reported by other mining companies operating in the regional area.

The permit application references a regional study of coal-aquifer hydraulic characteristics conducted at an adjacent mine operation. This study was based upon analysis of pit-pumpage records and groundwater drawdowns observed in many observation wells. This provided an excellent appraisal of the overall transmissivity of the coal, as it avoids the fracture variability factor encountered from a pump test at a single location.

Flow-net analyses are used in the permit application to determine directions of groundwater flow and areas of discharge in overburden strata. Pump tests were conducted during 1980 within the sandstone overburden and a sand body within the coal cut-out (no-coal channel). The tests were conducted to determine the hydrologic characteristics and the recharge potential of these features. Both tests utilized a pumping well and two observation wells. These results indicate that the overburden sand is highly transmissive and a logical source of recharge to the intermittent stream. The pump test in the coal cut-out indicated that the sands there are relatively impermeable.

Potentiometric surface maps were constructed for the sandy overburden and coal aquifers using water-level measurements taken during October 1978. The overburden potentiometric-surface maps were constructed from wells completed in both overburden aquifers and alluvium. The maps were used by the applicant to determine the regional direction of groundwater flow in the coal and overburden.

3.12.3.2 Analytical Techniques

Potentiometric-surface maps of the coal and overburden aquifers were used with flow-net analyses to determine rates and directions of groundwater flow and the effect on flow of the no-coal channel. Potentiometric elevations were compared to stream-channel elevations to determine areas where groundwater discharges to the stream. Flow net analyses are conducted in the manner described by Todd (1976) to estimate groundwater flow rates in aquifers and the rate at which groundwater recharges the stream system (see Section 2.4.2.1).

The applicant used a digital computer model to predict drawdowns in the coal aquifer due to their mining operations alone and the cumulative drawdowns due to all mining operations within the coal aquifer in the general area. The model was also used to estimate the time for the spoils to resaturate and the effects of the spoils on regional, postmining groundwater flow. This section describes that model, its use in this application, and assesses the data used.

The model chosen by the applicant to simulate the coal hydrologic conditions was developed by T.A. Prickett and C.G. Lonnquist for the Illinois State Water Survey (Prickett and Lonnquist, 1971). The Prickett-Lonnquist model, which is available in the public domain, utilizes a finite-difference approach to solve the groundwater equations for non-steady flow in a heterogeneous aquifer (see Section 2.4.2.1 and Appendix C). A modified alternating direction implicit method is used to solve the finite-difference equations defining the flow in porous media. This model was written in FORTRAN for mainframe computers but has been translated into BASIC by various individuals for use on smaller computers. The applicant in this case study used a mainframe.

The Prickett-Lonnquist model can simulate one or two aquifers under leaky or non-leaky artesian conditions or water-table conditions. Input data can include vertical recharge rates, variable pumpage rates or constant-head conditions. The model also has the capability of analyzing changes in aquifer transmissivities and storage coefficients resultant from conversion from confined to water-table conditions.

Data from drilling programs and aquifer pump tests were used in approximating hydrogeologic boundary conditions required in the model. It was necessary to assume that the thickness of the coal and coal parting material remain constant throughout the modelled area. The coal outcrop was considered a no-flow boundary. Great differences in transmissivities and storage coefficients exist between the coal and fine-grained clastic materials on either side of the cropline. Therefore, no flow of water from one material to the other was assumed to occur. A minor conflict was noted in the assigned boundary condition values wherein the strata beyond the coal cropline was assigned a constant groundwater recharge rate at the same time it was assumed to have a transmissivity of zero. This conflict likely had no effect on the operation of the model.

Constant-head boundaries were assumed to exist where streams have eroded into the coal seam. These points can be either discharge or recharge points for the coal, depending on the elevation of the coal potentiometric surface with respect to the stream bed. In either case it was assumed that the potentiometric surface of the coal will go no lower than the elevation of the contact between the stream and the coal.

After determining the boundary conditions in the vicinity of the mine, hydrologic parameters that could be applied to the entire permit area were chosen, based on pump-test data from the mine as well as data from an active mine immediately north of the permit area. These parameters were then applied to the entire model area. Initially, the coal was assumed to be confined throughout the entire model area.

Determining hydrologic parameters for the backfill was difficult. Aquifer characteristics have not been determined for the backfill wells because recharge to the backfill has occurred only very recently. Spoil permeability was estimated based upon the approximate lithologic composition of the spoils following procedures set forth by Cedergren (1977). The postmining saturated thickness of spoils was estimated based on premining groundwater elevations, and spoil transmissivity was estimated through a standard groundwater equation relating aquifer permeability and saturated thickness (after Todd, 1976).

To adequately model the drawdown due to mining in the coal aquifer, a grid of nodes large enough to include all of the area that might experience drawdown was established. The grid consists of an array of nodes spaced on 5280-foot (one mile) centers. Each node, and the aquifer values given to the node, therefore represents an area 5280 feet by 5280 feet, with the node located in the center. The size of the grid, 31 nodes east-west by 36 nodes north-south, and the node spacing of 5280 feet were chosen to fit the size of the area in which the applicant has acquired data (approximately one percent of the entire area) and the existing model (the standard Prickett-Lonnquist model is dimensioned for a 50 by 50 grid). The first runs were done with a 31 by 31 grid, but the model was extended 5 nodes (5 miles) to the south after initial run 1 indicated that drawdowns were approaching the no-flow boundary.

Drawdowns in the coal aquifer presently extend to the north, west, and south; however it was assumed that no drawdowns are possible in the area east of the coal cropline. Therefore, the grid was placed with its eastern edge along the edge of the coal cropline. The grid was also placed such that the mine was nearly centered on the north-south axis of the grid.

Special groundwater recharge nodes were assigned to several locations where the operator felt the recharge rate was greater than average. Two small lakes in the general area and closed depressions of approximately one square mile were initially given higher recharge rates. The calibration of the model, however, indicated water levels would build up above ground level in several locations, so recharge rates in those areas were appropriately lowered by trial and error. These lower values kept water levels below ground level, and were used to produce the modelled premining groundwater levels.

Several no-coal channels exist in the modelled area. Where the width of the channels are great enough to influence groundwater movement, then transmissivity, storage coefficient and recharge values reflecting the no-coal channels were put into the model at the node points.

A few nodes were designed as stream-discharge nodes. These nodes were assigned where water levels were building above ground surface in the calibration attempts. Assumed discharge values were assigned to these locations during calibration. All other nodes throughout the grid received constant values for water elevations, transmissivity and storage coefficient.

Calibration of the model involved adjusting groundwater recharge and discharge rates from the coal aquifer until the calculated premining groundwater levels in the coal closely matched those observed in monitoring wells.

After the model was calibrated, a sensitivity analysis was done to determine how the model responds to changes in the major parameters of transmissivity, storage coefficient and head. This analysis was used to evaluate the accuracy of the assumed values and as an aid in making additional assumptions required in the operation of the model.

Once the model was calibrated and the sensitivity analysis completed, the effects of mining and backfill on the potentiometric surface could be simulated. Simulation of mining at a node was accomplished by reducing the potentiometric surface in the coal aquifer to the elevation of the bottom of the coal at the node. In addition, the transmissivity was decreased to approximate the effects of coal dewatering near the mine pit. At all other nodes, the aquifer characteristics and recharge rates remained the same. Mine progression was simulated by lowering the potentiometric surface at different nodes during the corresponding time that each node was to be mined.

The effects of the backfill on groundwater flow were simulated by changing the aquifer characteristics at the appropriate nodes. Groundwater levels at the backfill nodes were initially set at the bottom of the coal aquifer and were allowed to recharge at a rate assumed to be indicative of the area's natural groundwater recharge rate and using a spoil permeability estimated through the assumptions described earlier.

Where any portion of a modelled node was affected by mining, it was assumed for the purposes of the computations that the entire nodal area would be mined instantaneously. That is, the groundwater elevation for the entire area represented by the node is reduced to that of the bottom of the coal at that node. In addition, it was assumed that once a node was backfilled it was instantaneously and entirely backfilled, and that recharge to the backfill could begin at that time.

Drawdowns in the potentiometric surface of the coal aquifer from activities at the one mine alone were calculated for the term-of-permit and for the life of the mine. Drawdowns in the potentiometric surface of the coal from activities at the seven mines in the general area were also calculated. The maximum extent of the five-foot drawdown for the life-of-mine will occur at different times for different locations, depending on whether mining is still occurring nearby or has been completed.

Postmining potentiometric surfaces in the coal aquifer and backfill were developed from the model. When only the one mine is considered, the model predicts that groundwater equilibrium will not be reestablished until over 100 years after mining has ceased. However, when all seven mines are considered, equilibrium conditions are met at different times for different mines but are all in excess of 400 years.

3.12.3.3 Monitoring and Reporting

Monitoring wells are measured at periodic intervals to record water levels. In a number of wells water levels are recorded continuously. During mining the frequency of monitoring will be evaluated according to distances of wells from mine pits. Several years' worth of data have been collected on a monthly or quarterly basis for most monitoring wells. Wells will be measured semi-annually in April and October, except for those wells so distant from the pits as to show no drawdown related to mining. These latter wells, which will not be near the limits of mining for a number of years, will be measured annually in October until mine pits approach them. When drawdown is noted in a well monitored annually, the monitoring of the well will be switched to a semi-annual schedule.

The applicant stated that backfill wells will be monitored quarterly to observe resaturation of the spoils. These wells will remain on a quarterly schedule until the recharge level stabilizes; at that time they will be monitored semi-annually. This monitoring period may be meaningless based upon the bond-release time frame and the estimated time for resaturation (potentially in excess of 400 years).

Once sufficient groundwater recharge has occurred, pump tests will be conducted in the backfill. Thereafter, tests will be conducted on selected wells at least once every two years to determine any change in the aquifer characteristics that may occur due to settling of the saturated backfill. Again, it is questionable whether sufficient resaturation of spoils will occur during the postmining evaluation period to allow many spoil pumping tests.

Field data from manual measurements and recorder charts are entered on a computer. The data can then be used to generate plots of water levels over time. Information on selected wells will be summarized in the annual report to the regulatory authority. Raw data will be kept on file at the operator's office in Gillette, Wyoming.

3.12.3.4 Evaluation Criteria

The results of the model study described herein were evaluated by the operator and the regulatory authority to determine:

1. extent of groundwater drawdowns due to mining, hence the area of potential impact,
2. amount of drawdown experienced in adjacent areas to ascertain the degree of impact to specific wells, and
3. areas where additional monitoring may be needed.

The model predicts that the drawdown impacts will be long-term, since spoils will not fully resaturate for 100 to 400 years. No specific criteria were presented to define what constitutes successful restoration or how it will be evaluated.

3.12.4 Identification of Issues

This case study serves to illustrate the advantages of the use of digital computer models over manual calculations to analyze hydrologic effects of mining. These advantages are described in Section 2.4.2.1 and summarized in Table 6. Because the computer simulation is able to handle a larger number of variables and development scenarios, it helps to eliminate the bias that results from worst-case analyses done through manual calculations. The digital model also helps to point out where critical data are lacking, and therefore it is a better planning tool.

The computer simulation illustrates another issue. By estimating that up to several hundred years will be required for groundwater levels to reach equilibrium conditions after mining, it points out uncertainties as to when any restoration evaluation criteria are to be applied.

No specific plans were presented to collect additional data to refine the computer simulations, although the model did serve to indicate where and how often additional data collection would be useful.

3.13 Case Study M

3.13.1 Focus

This case study examines surface-water monitoring and problems associated with carbonaceous overburden at a surface coal mine located in northeastern Wyoming.

3.13.2 Description of Mine and Hydrologic Setting

The study mine is a coal strip mine located on the eastern flank of the Powder River Basin in Wyoming. The mine is in the Belle Fourche River basin, south and east of the City of Gillette in Campbell County, Wyoming. Production is from the Wyodak coal seam, and the mining method is truck-shovel. The permit area covers about 6000 acres. The mine was opened in 1976.

One of the major streams in the region runs through the mining area and is an intermittent stream in that stretch. Six tributaries of the stream are also located within the mining area, of which five will be disturbed by the mining process. The tributaries to be disturbed are ephemeral. A short reach of an intermittent tributary to the major stream is within the mine-permit area and, except for one small draw, will be undisturbed by mining.

Annual flows through the mine area are small due to the semiarid climate (annual precipitation is about 15 inches). Most streamflow occurs in the months of February through September in response to late winter snowmelt and spring rainfall. The major stream does receive sufficient recharge from groundwater sources to make it locally intermittent.

Premining surface-water development is limited to a few stockwater ponds. Streamflows are too unreliable to allow irrigation development.

The overburden contains layers of carbonaceous material, and there are carbonaceous layers of parting material within the coal seam. Carbonaceous material is a concern in mine spoils because it contains pyritic sulfur and organic sulfur which can produce acids when oxidized.

The regulatory agency has expressed concern about placement of carbonaceous material in areas below the postmining water table during mine backfill because of the possibility of producing acidic groundwater.

3.13.3 Presentation of Case Study

3.13.3.1 Baseline Data

In order to quantify the baseline, or premining, surface-water resources on and near the permit area, 68 crest-stage gages with single stage sediment samplers (34 crest-stage gage pairs), one crest-stage gage without a sediment sampler, and four recording V-notch weirs with automatic water quality samplers were installed in 1981. These surface-water monitoring stations were to complement the existing monitoring network, established in 1976, which consisted of two instrumented weirs with automatic water-quality samplers, an instrumented Parshall flume with automatic sampler, and two USGS gaging stations located upstream and downstream of the permit area on the main stem of the major intermittent stream.

Two recorders were placed at sediment pond outfalls to record NPDES discharges. To date, no discharges have been recorded at either site. Five additional reservoirs are being monitored for water quality. Outflow from three of the reservoirs is monitored by recorders.

The four recording weirs installed in 1981 were located on the intermittent tributary to the major stream and on three ephemeral tributaries. The two recording weirs established in 1976 were located on ephemeral tributaries. The Parshall flume was removed in 1981 at the time the additional recording weirs were installed. In 1983, one of the weirs on an ephemeral tributary was determined to be unnecessary and was removed. In the spring of 1984 the weir on the intermittent tributary washed out and is currently not operating. In addition to the surface-flow records obtained from the gages installed by the mine and the USGS stations located near the mine, the records from three other USGS gaging stations in the same drainage basin were used by the applicant to establish baseline streamflow characteristics.

Rating curves were developed for each crest-stage gage using the USGS Slope-Area Method (Dalrymple and Benson, 1967). Channel cross sections were surveyed at each crest-stage gage pair and 50 feet upstream and downstream of the gage location. Peak flows were estimated using the SCS TR-20 runoff simulation model. Water surface elevations were then computed for each flood event using the slope-area method to develop the rating curve for each gage.

No data were collected from the surface-water monitoring system in 1981, the year of installation. Data have been collected for the years of 1982 and 1983 and published in the mine's annual report. The USGS stations above and below the mining area have been in operation since October 1975, with daily records published annually. Data from the weirs are published in the permit application. Because of the ephemeral or intermittent nature of streams being monitored within the mine-permit area, flow data from the surface-water monitoring stations are limited.

Flows were recorded in drainages with crest-stage gages on five days in 1982 and one day in 1983. Crest-stage gage data were not available for 1984 at the time this report was being prepared.

Records for the USGS gaging stations in the area are published in the annual USGS Water Resources Data Report for Wyoming. Flow data are published on a water-year basis, and calendar year 1983 and 1984 data were not yet available at the time of this report.

Flow data collected from the recording weirs to date are difficult to use because of inconsistencies in numbering of the weirs. This is particularly a problem with respect to weirs on two of the ephemeral tributaries. The weir numbers shown on the map of the surface-water monitoring system do not correspond with the numbers given in the annual reports.

Data from the weirs are published in a summary table which shows the number of days that flow occurred, annual peak flow and date of occurrence, and total annual runoff volume.

Crest-stage gage pair data are presented in tables showing the date of flow, peak discharge computed using each of the gage heights, and TSS at each of the single-stage samplers at the station site for each runoff event. The crest-stage gage data are of little use because of the method used to reduce the data. Rather than using the peak stage reading at each gage in a pair to calculate the estimated peak discharge in the reach, in accordance with standard USGS procedures (Dalrymple and Benson, 1967), the applicant calculated a different peak flow for each gage in the pair. Peak flows at two gages in one installation vary by as much as 800 percent, and variation is higher at higher flows. The data have been submitted in this format to the regulatory authority for at least two years.

The overburden at the mine site was assessed prior to mining to identify its physical and chemical properties. The assessment program consisted of drilling and coring of the overburden, sampling of regraded backfill, and establishment of backfill-material test plots.

Identification of toxic and acid-forming materials within the overburden was done using guidelines of the regulatory agency.

The drilling and coring program was conducted in three phases. The initial phase, in 1975, consisted of drilling seven overburden holes spaced along the north and west sections of the permit area. Seven cores were saved for laboratory analysis in the first phase.

In the second phase, beginning in June of 1980, ten additional holes were drilled in the overburden. Overburden cutting samples were collected at five-foot intervals. The samples were sealed and sent to a laboratory for analysis.

In 1981, the third phase of the program began. The seven overburden cores collected in 1975 were analyzed in a laboratory. Two new holes were drilled within twenty feet of two of the 1975 holes to collect samples for cross checking with the 1975 core samples. In addition, twenty-two overburden holes were drilled to provide additional data requested by the regulatory agency. Cutting samples were collected from eleven of the holes, nine core samples were taken, and two core/cutting combination samples were collected. Drill holes are spaced fairly evenly over the entire mine-permit area at approximately 180 acres per hole.

The cutting samples and cores collected during the drilling program were analyzed for the following parameters:

Saturation percentage
pH
Conductivity
Calcium
Magnesium
Sodium
Lead
SAR
Lime ($CaCO_3$)
Nitrate
Potential acidity
Neutrality potential
Acid-base potential

In addition, selected samples were analyzed for:

Texture
Organic matter
Molybdenum
Boron
Copper
Selenium

A total of 757 samples were analyzed during the overburden suitability assessment.

As a result of the overburden assessment program several carbonaceous layers have been identified at the mine site. Carbonaceous material is defined by the regulatory agency to be black material with an organic carbon content, as determined by the Walkley-Black test (Agronomy Society of America, 1965), of greater than ten percent. Carbonaceous material in the permit area typically consists of clay or shale.

There are two consistent parting layers in the coal seam. The upper parting is approximately fifteen feet below the top of the coal and consists of a layer of soft clay or harder shale surrounded by ash. The clay and shale are typically carbonaceous. The lower parting consists of soft, carbonaceous clay often grading to gray clay and sand. Surrounding the partings are zones of coal with high ash content. A third parting occasionally occurs below the lower parting.

Two additional coal partings occur in the northeastern and southern portions of the permit area. Both occur near the base of the coal. These local partings are composed of hard, carbonaceous shale which locally grades to non-carbonaceous shale. In addition to the carbonaceous material contained in the Wyodak seam parting layers, thinner seams of coal above the Wyodak also contain carbonaceous shale as does the underburden immediately below the Wyodak seam.

3.13.3.2 Analytical Techniques

Baseline data collected under the hydrologic monitoring plan were used only to a very limited extent in determining impacts to the surface-water system resulting from mining. This is because little data has been obtained (see Section 3.13.3.1), the analytical techniques used to predict surface-water impacts do not rely on streamflow data (see discussion below) and, as described later, the data from the crest-stage gages were incorrectly reduced.

The majority of the projected impacts were determined using proposed changes in drainage-basin characteristics and the probable results of those changes. Changes in the soil cover on the disturbed drainage basins were predicted to have an effect on runoff from the basins. Potential impacts on runoff were projected by comparing premining soil conditions and postmining soil conditions and using the results to develop input data for the TR-20 computer model (see Section 2.3.2.1). Premining soils were distributed with coarse-textured soil on upland regions of the basins and fine-textured soils in the lower, flatter regions. According to the applicant, reclamation will result in a uniform soil texture over the entire basin, and runoff will decrease for a period of years until the finer-textured soils are moved to the lower regions of the basins and infiltration characteristics are redistributed to approximate premining conditions.

Postmining topography will be more gentle than the premining topography. The reduction in gradient of the upper portions of the basins will reduce runoff, erosion, and sediment yield. The applicant states that impacts to streamflow and sediment yield downstream of the mining area will probably be masked by dynamic changes in stream geomorphology in natural channels in the area.

By comparison of drainage areas, impacts to streamflow in the major drainage were predicted to be minor. The maximum mine disturbance area is a small portion of the total drainage area of this large stream. Reductions in water yield from the mining area would only have an effect upon a small percentage of the flow in the stream.

Baseline data for the premining drainages were used to prepare a hydrologic balance for the premining soil horizon (see Section 2.4.2.3 and example in Section 3.16). Measured runoff values were used to estimate effective precipitation from precipitation records. The water balance is typical of a semi-arid environment, with the majority of the precipitation captured in the soil profile and consumptively used by vegetation. Postmining water balance is predicted by the operator to be similar to the premining water balance.

The baseline data collected under the hydrologic monitoring plan were not used in the design of surface-water reclamation features. Design of the reclaimed channels within the mining area was done using flows computed by the SCS TR-20 computer model. This model, as described in Section 2.3.2.1, uses site-specific soil, vegetation and drainage-basin characteristics (size, relief and hydraulic length) and regional precipitation frequency-duration data. Computed peak discharges for the 2-year 1-hour and 100-year 24-hour storms were used in the design.

Channels were designed with a pilot channel and a flood plain. The pilot channel was designed to convey the 2-year, 1-hour storm runoff. The flood plain was designed as if the pilot channel were not there in order to simplify calculations and provide a conservative estimate of the capacity of the combined channel. Design capacity of the flood plain without the pilot channel is the 100-year 24-hour storm peak discharge.

Erosion is to be controlled in the pilot channels by limiting the maximum water velocity. The gradient of the channel and the channel geometry were adjusted until velocity in all reaches was below a value that was considered non-erosive. Stability of the pilot channels was evaluated using information presented in Fluvial Processes in Geomorphology (Leopold, Wolman, and Miller, 1964). Width-depth relationships for streams in the area were used to determine the ratio of channel width to flow depth typical of streams in the area. These ratios were used in pilot-channel design.

Hydraulics for channel restoration were determined using the uniform flow equation and an assumed roughness factor. The roughness factor was chosen to be representative of earth channels with grass and sparse brush vegetative cover.

Ten stockwater reservoirs will be constructed as part of the surface-water reclamation procedures. Design of the stock ponds will also be based on runoff calculated using the SCS TR-20 model.

Basin drainage characteristics to be restored include drainage area, drainage density, channel gradients, and maximum basin relief (see Section 2.3.2.4). Potholes will not be replaced in the postmining channels, although they may redevelop naturally with time.

Overburden at the mine was analyzed using techniques suggested in regulatory agency guidelines. The acid-base potential (ABP) is the typical analysis used to determine the acid-generating potential of mine spoils. The ABP of a soil sample is calculated by determining the total sulfur content of the sample through oxidation of the sulfur to produce acid, determining the amount of acid produced, and then reducing the amount of acid produced by the amount of neutralizing bases in the soil.

The total sulfur available to produce acid is determined by removing inert sulfates from the sample by washing it out with a weak acid. The remaining sulfur is oxidized by one of two methods, a LECO furnace or hydrogen peroxide (H_2O_2), to produce acid. The hydrogen peroxide method is much less accurate than the LECO furnace method but is widely used because many laboratories do not have a LECO furnace.

The ABP method was developed using spoils from coal mines in the eastern United States. The overburden from eastern coal mines contains sulfur almost exclusively as inorganic iron pyrite, with very little of the sulfur content made up of organic compounds. Western coal mine spoils, including those at the study mine, contain sulfur mostly in organic compounds. Pyrite in western mines seems to have a threshold value of 22 percent of the total sulfur content, which is not exceeded no matter how high the total sulfur content of the overburden (Dollhopf, 1981).

The high percentage of organic sulfur in western coal mine spoils causes errors in the determination of ABP using the hydrogen peroxide method. Pyritic sulfur produces approximately four times as much acid as organic sulfur compounds. The LECO furnace oxidizes only the pyritic sulfur, while the hydrogen peroxide oxidizes both pyritic and organic sulfur. The ABP methodology was developed using the LECO furnace, assuming that organic sulfur content of the soil is very small.

When hydrogen peroxide is used to oxidize the sulfur, the ABP indicates higher acid-generating potential than is actually the case.

The ABP of carbonaceous material at the mine was calculated using both the LECO furnace method and the hydrogen peroxide method. Results with the LECO furnace method indicated that the acid-producing potential of the material is low, while the hydrogen peroxide method indicated that the acid-producing potential is high. Since the organic matter content of the overburden is extremely high, the applicant considered it likely that the ABP calculated using the hydrogen peroxide method is inaccurate.

Because the peroxide method for determining ABP is questionable, the applicant developed a correlation curve to determine ABP suitability. A good relationship was found between the peroxide method and the LECO furnace method. The correlation curve developed was approved by the regulatory agency. Based on this curve, the applicant and the regulatory authority reached an agreement as to an unsuitability criterion for ABP. Materials found to have ABP values greater than -100 tons $CaCO_3$ equivalent/1000 tons using the peroxide method will be considered to have positive ABP using the correlation. Materials with ABP less than -100 using the peroxide method will be treated as unsuitable until further analyses show it to be suitable. Areas which change from unsuitable to suitable as a result of the correlation will be reanalyzed on the basis of one hole per 160 acres for the area in question. If the additional analyses indicate that the overburden is suitable, the original data will be discounted and the overburden will be considered suitable. If the additional analyses indicate that the material is unsuitable, the mining company may either consider it unsuitable and place the material below the top four feet of regraded backfill or may conduct further analyses on the basis of one hole per forty acres to further define the extent of unsuitable material.

The study mine is presently mixing the carbonaceous material with materials that have high base potential to dilute the acid-producing potential of the backfill. Previous studies (Dollhopf, et al., 1981) have shown that when less than fifteen percent of the overburden consists of unsuitable materials, the unsuitable materials can be diluted successfully by mixing with a dragline operation. The mine is experimenting to determine if a truck-and-shovel operation can achieve the same success. The operator pointed out that mixing is a viable solution because carbonaceous materials have historically been placed in the pit with no adverse effects on water quality.

3.13.3.3 Monitoring and Reporting

The postmining surface-water monitoring network will be the same network as the premining and during mining networks. Crest-stage gages will be removed as the mining reaches them and then replaced in the approximate premining locations within one month after final backfill and channel reestablishment. The USGS stations and four of the five existing instrumented weirs have been located in areas which will not be disturbed by mining. One weir will be removed during mining operations but will be replaced after final channel restoration.

A monitoring-well network of 23 wells will be established in the backfill to monitor recharge of the spoil aquifer and to monitor changes in water quality. Wells will be monitored quarterly for the duration of the mining and for five years following final reclamation.

Results of the monitoring program are to be published in the annual reports of the mine.

A sampling program has been developed to assure that the top four feet of the regraded backfill consists of suitable material. Samples are tested for all parameters in the regulatory agency guidelines (Table 8). By agreement with the regulatory authority, black or carbonaceous material is acceptable in the top four feet of the backfill as long as the average composition for any 5-acre area does not exceed suitability criteria.

3.13.3.4 Evaluation Criteria

The postmining drainage system will be approximately the same as the premining system. Drainage area, drainage density, channel gradients, and maximum basin relief will all be restored as nearly as possible to premining conditions. The terrain of the postmining area will not be as rough as premining terrain. Average basin sideslopes will also be reduced to some extent. Evaluation of this plan consists of comparison of drainage-basin characteristics developed from premining and postmining topographic maps.

Mining and reclamation work have not yet progressed to the point where an evaluation of the reclamation plan can be made using data from the monitoring network. The monitoring system is designed to provide pre- and postmining information for comparison. Determination of the impacts of mining upon the surface-water system will be difficult, however, because of the nature of the system. The application states that differences between premining and postmining runoff characteristics will be so subtle that effects of mining will not be easily distinguished from those caused by natural climatic variations. Although monitoring is proposed, no criteria are in effect with which to compare the monitoring data to evaluate surface-water reclamation success.

The regulatory agency has agreed to allow the mining company to place carbonaceous material determined to be unsuitable beneath the postmining potentiometric surface and within the top four feet of regraded overburden during the present permit term. The practice will be allowed to continue provided that:

1. a representative sample of overburden within the top four feet of regraded spoil in any 5-acre area meets state suitability criteria, and
2. spoil-water quality is found to be acceptable.

A problem with the second evaluation criterion listed above is that no numerical standards were established to determine acceptability of spoil-water quality. Presumably, the evaluation criterion will be no change in use-suitability (see Table 1).

3.13.4 Identification of Issues

The extensive surface-water monitoring network at the mine site will provide information about the drainage system that would not otherwise be available. The applicability of the monitoring data to the problem of determining and mitigating impacts to the site-specific and regional surface-water system is questionable, however. Flow data collected over a relatively short period of time on ephemeral and intermittent streams will not provide a database sufficient to quantify impacts to the area because of the low frequency of streamflow occurrence and extreme variability in streamflow typical to such an area. Also, the data collected are not very useful in the form in which presented, and in fact it appears there were errors in reduction of crest-stage gage data which went undetected by the operator and the regulatory authority for at least two years.

The crest-stage gage monitoring program was installed at the request of the regulatory agency. Data collected from the program to date has not been useful because of the inconsistent results and errors in data reduction. Maintenance of the crest-stage gage stations has been difficult, and some of the data inconsistencies may have resulted from maintenance problems. The applicant has proposed removal of the crest-stage gage monitoring network and the regulatory agency has concurred. Removal of the network will probably be implemented at the time of the next permit application revision.

The operator has provided a study that indicates that a method widely used to determine acid-base potential (ABP) of overburden at coal mines in the western U.S is inaccurate. The high organic content of soils in the western U.S. as compared to the soils in the eastern U.S., for which the methodology was developed, results in calculated acid-producing potential which is much greater than the actual acid-producing potential of the soil when hydrogen peroxide is used to oxidize the sulfur in the soil sample.

The carbonaceous overburden issue at this mine and the agreement between the operator and the regulatory authority as to how it should be addressed is an example of comprehensive utilization of baseline and monitoring data to predict reclamation results and to provide a means for eventual evaluation of reclamation results.

3.14 Case Study N

3.14.1 Focus

The Wyoming surface coal mine discussed in this case study recently expanded its operations to a new area. Permitting of the new portion of the mine occurred after the advent of SMCRA and after the State and Federal regulatory framework had been established. The purpose of this case study is to illustrate the increased efficiency of the permitting process brought about by finalization of regulations and guidelines.

3.14.2 Description of Mine and Hydrologic Setting

The study mine is a coal strip mine located approximately six miles north of the City of Gillette in Campbell County, Wyoming. The mine is on the eastern flank of the Powder River Basin in the area where the Fort Union and Wasatch Formations crop out at the surface. Production is from the Wyodak, or Roland-Smith, coal, and mining will be done with trucks and shovels.

The permit area is located near the headwaters of a major regional drainage system. There are also several small closed drainage basins within the permit area. All of the streams within the permit area are ephemeral.

The major aquifer in the vicinity of the mine area consists of clinker or scoria deposits overlying the coal beds. The clinker is not continuous throughout the mine area because of interruptions caused by faults and coal islands, and saturated thicknesses vary from zero to several tens of feet.

The coal beds also act as aquifers within the permit area. Transmissivity of the coal aquifers is much less than that of the clinker aquifers. Sand channels exist in the mine area where coal has not been deposited or where deposited coal has been eroded away. The sand channels are low-yield aquifers like the coal, but have generally lower transmissivities. Overburden aquifers, which consist of discontinuous sandstone lenses in the Wasatch Formation, generally have the lowest transmissivities within the permit area.

A small area (15 to 20 acres) of the largest drainage in the permit area has been declared an alluvial valley floor not significant to farming. The alluvium within the permit area extends in a narrow band on each side of the channel, and is relatively shallow. Surface-water availability is not sufficient for flood irrigation. The water table in the alluvium is near the land surface on either side of the channel indicating some potential for subirrigation. Transmissivity of the alluvial aquifer is similar to the more permeable areas of the coal aquifer.

3.14.2.1 Baseline Data

The surface-water drainage system of the permit area was divided into sub-drainage basins for geomorphic analysis. Each of the basins was analyzed with respect to runoff quantities, water-quality parameters, stream-channel characteristics, and drainage-basin characteristics. Information on drainage basin characteristics was collected by an extensive field survey of the permit area. Data were collected on drainage area, drainage density, basin slope, and drainage length. Topographic maps of the permit area with five-foot contour intervals were prepared and used to develop the basin data. Data were also collected from work done for several adjacent mines in the area and compiled for use in the study. Streamflow data were collected from regional reports prepared by the USGS and other state and Federal agencies to characterize the surface-water system and describe the hydrology of the general area.

Stream-channel characteristics were developed by surveying cross sections of the major drainage channels in the area. Longitudinal profiles of the major streams were prepared using topographic maps of the permit area and the surveyed cross sections. Erosion characteristics of the channels were determined using soil surveys of the permit area and supported by a reconnaissance of the area to identify areas of headcutting, scarps, and sandy channel bottoms.

A surface-water monitoring program has been underway at the mine for several years. Five crest-stage gages were installed in 1978 by the former owner of the property. Only one flow event has been recorded at three of the gages and two have not recorded any flows to date. A weir with water-level recorder was installed on the largest stream below the mine-permit boundary in 1978. No flows have been recorded at the weir since its installation.

Streamflow information for the permit area, included in the permit application, is incomplete and of limited use. The data are based on an arbitrary gage datum, the method of estimating peak discharge is not discussed, and no information was given on the precipitation events that caused the runoff for the few runoff events that occurred.

In addition to the flow-measuring stations within the permit boundary, data are collected on streams adjacent to the permit area by other mining companies. A Parshall flume with a water-level recorder was operated on a minor tributary below the permit area for a period of approximately six years. Daily streamflow records from the station are presented in an addendum to the hydrology section.

Three pairs of crest-stage gages and a stock pond staff gage were installed on other ephemeral streams in the area as part of the permitting process for an adjacent mine. Data from these gages were not included in this permit application but were submitted to the regulatory agency by the operator of the other mine. Data collected in the future from the crest-stage gages and the staff gage will be used to supplement the monitoring-program data.

Regional streamflow characteristics were determined using data from USGS and mining company streamflow gages in the general area. Information on the yearly distribution of runoff, runoff per unit area, and the seasonal distribution of runoff was developed using the regional data. Precipitation data for the mining area were collected from the NOAA weather station at Gillette.

Both regional reports and rainfall-runoff calculations were used to compute streamflow characteristics within the permit area.

The groundwater system within the permit area was analyzed through an extensive network of test holes and monitor wells. Ten geologic cross sections of the permit area were developed from logging data and core samples taken from test holes. A total of 96 test holes were drilled to define the geology of the permit area.

Monitor wells were drilled and cased in aquifers in the permit area to collect groundwater level data. The number of wells drilled is not easily determined from the permit application. Information is given for 84 wells in the text of the hydrology section, but water-level data are given for fewer wells in the addendum to the appendix. The majority of the monitor wells were completed in 1977 and 1978 and water-level data are available for most of them from 1978 through 1981. Water-level measurements were apparently made at least quarterly during the period 1978-81 with additional measurements taken at random. A single measurement was made in 1982 and in 1983 for most of the wells.

Data on aquifer properties were collected through pump tests of wells completed in the different types of aquifers. Properties of the alluvial aquifer were determined by a multiple-well pump test. The channel-sand aquifer, coal aquifer, and overburden-aquifer properties were analyzed using multiple-well and single-well pump tests. Drawdown and recovery data were collected for the pumped well in single and multiple-well tests and for observation wells in multiple-well tests. Water-level variations with time were also compared with changes in barometric pressure. Pump-test analyses were based on widely accepted techniques.

Groundwater quality data were collected from 63 monitor wells in the permit area. Sampling began in 1978 and continued for differing lengths of time at each well. Samples were taken twice yearly during the periods when sampling occurred. Wells were pumped or bailed until conductivity and temperature of the water stabilized before samples were taken.

Water quality measurements taken in the field included temperature, conductivity, pH, bicarbonate, and visual oil and grease. Parameters tested for in the laboratory included those suggested by the regulatory agency (Table 4). All laboratory samples were filtered and preserved using techniques outlined in the regulatory-agency guidelines.

Some regional groundwater quality data were available from the USGS for the Wasatch and Fort Union Formations. TDS concentrations for aquifers in the formations in northeast Wyoming were published in a USGS Atlas (Hodson, 1973).

Potential alluvial valley floors within the mine-permit area were identified using data collected by adjacent mining companies in the area and by investigations within the permit area. Investigations of potential alluvial valley floors were conducted by mining companies located downstream of the mine-permit area. These data were compiled and analyzed to determine if AVFs extend into the permit area.

Test holes were drilled in the valley floor of the major drainage to further define stream laid deposits in that area. The depth of the water table was determined at each of the test holes, and indicator species were mapped to estimate the extent of subirrigation. Directions of groundwater flow and quantities of flow in the alluvial deposits were estimated to determine relationships between the alluvial aquifer and adjacent aquifers. Water-quality data were also collected for a well completed in alluvial deposits of the stream to determine suitability for irrigation.

As a result of the investigations, one potential AVF was identified within the permit area. Additional data were collected in that area. Ten test holes were drilled to develop geologic cross sections. Two of the test holes were cased for pump testing of the alluvial aquifer. Another set of three holes were established as monitor wells to monitor the gradient across the alluvium. Wells are monitored on a quarterly basis.

3.14.3.2 Analytical Techniques

The surface-water drainage systems was analyzed using methods developed by Horton (1945). Drainage densities were determined for each of the significant drainage basins in the permit area. All of the drainage densities are fairly close to the average value determined by Hadley and Schumm (1961) for drainages developed on the Wasatch Formation in the Cheyenne River Basin. Constants of channel maintenance were developed for third order and greater streams within the permit boundary.

Hypsometric curves were drawn for each major drainage basin to determine the erosional development and stability of the permit area. The hypsometric curves also illustrate the distribution of slopes and land mass within each basin. The maturity of each of the drainage basins and their position in the erosion cycle were estimated using the hypsometric curves (refer to Section 2.3.2.4).

Mean annual flows for each of the drainage basins were estimated using a regional drainage area relationship (Hadley and Schumm, 1961). The relationship between drainage density and mean annual flow was used to check for consistency in the determination of mean annual flows. The majority of the drainages in the permit fit the typical relationship.

Aggradation and degradation of the stream channels were analyzed using channel configurations. Sinuosity was determined from the topographic maps of the area and width-depth ratios were calculated from surveyed channel cross sections. Channel-configuration data were correlated with other basin characteristics to determine areas of potential erosion and deposition.

The analytical techniques described above and used to characterize the premining surface-water drainage system provide an indication of the stability of the drainage system. This information was used in the development of the reclamation plan to insure that impacts to the system would be minimized. Because the system is at or near equilibrium in the mine- permit area, the applicant concluded that it should be possible to minimize the impacts.

Surface-water records in and near the permit area are not of sufficient length to provide a database from which to estimate surface-runoff quantities and peak discharges. Therefore, flood estimates for the permit area were computed by an indirect method. The SCS triangular hydrograph method was used for drainages in the mine area.

Runoff potential was determined for the permit area using data from a SCS soil survey (1955) within the drainage area. The drainage areas were divided into hydrologic soil groups and the areas of each group were determined. A weighted runoff curve number was determined for each watershed and minimum infiltration rates were estimated using information in Design of Small Dams (USDI-BR, 1977). Direct runoff values were computed for six storm return periods--2, 5, 10, 25, 50 and 100 years. The direct runoff values were applied to a unit hydrograph to obtain storm hydrographs for each drainage basin. Peak flows as well as runoff volumes were obtained for the 24-hour storms with the six return periods.

Peak flows and runoff volumes used to design sediment control ponds and reclaimed channels within the permit area were obtained by the use of a computerized version of the SCS method (TRIHYDRO, see Section 2.3.2.1). Ponds were designed to contain the 10-year 24-hour runoff event. Channels were designed to carry the 2-year 24-hour runoff event in a guide channel at non-erosive velocities under conditions of little vegetative cover and without overtopping under conditions of fully established vegetative cover. The flood plains of the reclaimed channels were designed to carry the 100-year 24-hour runoff event without eroding or overtopping. Velocities were designed to be high enough to prevent sediment deposition.

Restored channels will be constructed as the overburden is replaced during mining. Final channels will be constructed as topsoil is placed over the regraded backfill. All channels will be revegetated to provide for erosion protection and simulate premining conditions.

Drainage-basin characteristics were designed to simulate premining conditions. Slopes will be reduced over most of the mining area, but computations showed that peak discharges will not be changed to a great degree.

Permanent impoundments will be created in the permit area. These ponds were sized to contain the 10-year 24-hour storm runoff volume as well as at least 10 years of sediment accumulation. The ponds will be used as sediment ponds to capture sediment and runoff from reclaimed areas during the life of the mine. After final reclamation, the ponds will be left in place as stock ponds to support the use of the reclaimed land as rangeland. The applicant used estimates of mean annual flow based on regional studies to show that the ponds should fill nearly every year and will spill often enough to maintain water quality by flushing.

Groundwater level data obtained from the monitor wells were analyzed to determine hydraulic connections between aquifers. Potentiometric contour maps were developed for the permit area for use in determining directions of groundwater flow.

Groundwater drawdown over the life of the mine was estimated using predicted inflows to the mine pits and a computer model of the aquifers in the mine area. Inflows to the mine pits were calculated using the Theis equation and aquifer parameters determined from the pump tests. The entire saturated thickness of each aquifer was assumed to be fully penetrated during the time the pit would be open. The length of exposed pit wall was estimated as two times the pit radius times pi and was assumed to remain constant throughout the duration of mining in the pit. In other words, the problem was simplified by assuming that the mine pit would function as a large, circular well (see Section 2.4.2.1 and Table 6).

The pit inflows were modeled as simulated wells pumping at a constant rate at each of the pit locations to estimate drawdowns. The computer model used the Theis equation to sum drawdowns from the simulated wells at each pit location. This was not a complex digital model but simply a computer program that solves the well-known Theis equation and uses the principle of superposition. That is, drawdowns computed at any point resulting from pumping at a group of wells is equal to the sum of the drawdowns computed at that point from each individual well. Many such programs have been written by consultants and companies for their own use and many others are available for purchase from software vendors. A well with an injection rate equal to the pumping rate (image well) was used to simulate the effects of ceasing pit dewatering in each pit. Drawdowns calculated using this method may be conservatively high because the method does not take into account effects of the change from confined to unconfined storage in the aquifers as drawdowns bring the water surface below the top of the coal aquifer. There was no discussion in the application as to how well the assumptions were met that are assumed by the use of the Theis equations. These assumptions include aquifer homogeneity, isotropy, infinite areal extent, infinitesimal well diameter, and constant coefficient of storage (see Section 2.4.2.1 and Table 6).

Cumulative drawdowns in the area due to the drawdown from mining in adjacent areas were estimated by adding the drawdown at the end of life of the mine, which is the worst case situation, to predicted drawdowns from other mines taken from the respective permit application documents. A contour map of predicted drawdowns was developed for the general area.

Groundwater quality samples were analyzed for required parameters (Table 4) using laboratory techniques specified by the regulatory agency. Changes in groundwater quality with time were analyzed to estimate recharge rates and groundwater flow patterns. Spatial variations in groundwater quality were analyzed to determine hydraulic interconnections between aquifers and patterns of groundwater flow.

Potential changes in groundwater quality caused by leaching of constituents as groundwater moves into the backfill material were determined by a batch test of an overburden core. A groundwater sample was mixed with the overburden sample for 48 hours and a solution was extracted from the mixture. An analysis of the solution indicated that changes in water-quality parameters should be less than ten percent for any one parameter (see Section 2.4.2.4).

The regulatory agency has stipulated that column-leaching studies (see Section 2.4.2.4) be performed on representative samples of the overburden material that will be placed below the postmining water table to demonstrate that adverse impacts on postmining water quality are "minimized" by the applicant. If the handling of unsuitable overburden presents undue hardships, the mine operator may also subject representative samples of the unsuitable overburden to column-leaching studies to demonstrate that placement of this material below the water table will have no adverse impacts on water quality.

The alluvial valley floor located in the permit area was analyzed using some of the same techniques that were used to analyze the groundwater system. Monitor wells were drilled to estimate the area of AVF where the water table is near enough to the surface to be used for subirrigation. Water in the alluvium was analyzed for chemical suitability for irrigation purposes. In addition, results of a multiple-well pump test were analyzed to obtain hydraulic characteristics of the alluvial aquifer.

Analytical techniques used to analyze premining data and estimate impacts to the surface-water and groundwater systems were chosen to meet guidelines prepared by State and Federal regulatory agencies. The acceptability of the techniques was therefore assured. Use of techniques acceptable to the regulatory agencies resulted in increased efficiency in preparation and review of the permit application.

Technologies and methodologies used in the design of the hydrologic features to be restored were also chosen using guidelines prepared by regulatory agencies. Guidelines were available for hydrologic restoration of the permit area because of the lack of outstanding hydrologic features which would require specialized technology. Preparation of the permit application as well as the regulatory agency review process were facilitated due to the use of conventional analytical techniques.

3.14.2.3 Monitoring and Reporting

Surface-water data to be collected on ephemeral streams includes crest-stage gage data and TSS concentrations. Water-level recorders and automatic water-quality sampling equipment will be installed on some of the larger ephemeral streams to collect additional information. Data from surface-water monitoring stations of other mines adjacent to this mine site will be obtained to provide information about impacts resulting from mining activities and will also be reported quarterly. The surface-water monitoring program will be continued until 5 years after final reclamation.

Groundwater monitoring will also continue until five years after final reclamation. The postmining monitoring network will consist of seventeen wells, nine of which are existing wells which will not be disturbed by mining and eight of which will be completed in the backfill to measure backfill water levels and quality.

Water levels in wells will be measured quarterly. Twice each year for the first two years and once each year thereafter, water-quality samples will be collected from each well and analyzed for the full list of parameters in WDEQ guidelines. A reduced list of constituents will be analyzed during the remaining quarters. Reports of monitoring results will be submitted quarterly.

3.14.2.4 Evaluation Criteria

The potential for successful reclamation of the mine surface-water drainage system was evaluated through drainage-basin analyses using premining and postmining topographic maps. Drainage basins within the mining area were studied in detail and found to be relatively stable. The reclamation plan was designed to enhance the stability of the drainage basins by restoring those drainage characteristics which contributed to the stability of the system and by replacing unstable features of the premining system with reclaimed features designed to be stable in the future.

Criteria to be used in evaluation of the success of mine reclamation include erosional stability of the drainage system, maintenance of channels during extreme runoff events, minimum water-quality changes as compared to premining water quality, and maintenance of drainage-basin water production. The applicant has committed to continuation of the surface-water quantity and quality monitoring program throughout mining and reclamation. The stated goal is to help determine when reclamation is complete for bond release purposes, although no quantitative standards were listed in the application to help with this evaluation.

The monitoring program has been established in accordance with State and Federal regulations but may not be of much use in evaluating the success of the mine reclamation plan. Continuation of the current surface-water monitoring will result in little additional data because of the ephemeral nature of the streams and the semi-arid climate of the area. Monitoring stations have recorded very few flows to date, and the frequency of runoff events will probably not change appreciably in the near future. No relationship is being developed between precipitation, runoff, and sediment transport. It is unlikely that five years of data collection following reclamation will establish a database that is sufficient to enable conclusions as to the success or failure of reclamation of the surface-water system, unless additional analyses of channel geometry are used in combination with the monitoring data to determine stability of the channels.

Evaluation of the success of reclamation of the groundwater system will be based on results of monitoring of groundwater quantity and quality. Groundwater levels in the reclaimed area will be monitored to determine the rate of water-level rise in the backfill aquifer. Groundwater quality will be monitored to record changes from premining conditions. The proposed column-leaching studies will be used to help predict whether adverse impacts to water quality will occur. No quantitative postmining water quality criteria were given with which to compare the monitoring results to evaluate whether restoration of the groundwater system is successful.

The groundwater monitoring program to be established following reclamation may also be of little use in establishing a database from which conclusions can be drawn regarding the success of aquifer restoration. The estimated time period required for recovery of water levels in the backfill is at least 100 years. The five-year time period for postmining monitoring may not be long enough to obtain any data.

Reclamation of the small portion of alluvial valley floor within the permit area will be evaluated with respect to restoration of the hydrologic functions of the alluvium. Water levels in the alluvium will be monitored to determine if they recover to a depth sufficient to maintain sub-irrigation on the valley floor to the extent it occurred before mining. Quality of water in the alluvium will also be monitored for irrigation suitability.

3.14.3 Identification of Issues

Review of this permit application and the associated correspondence between the applicant and the regulatory authority indicated that the review and approval process was efficient and was completed in a relatively short time. Several factors no doubt contributed to this, including a lack of any significant environmental or hydrologic features and location of the mine adjacent to three other existing or proposed mines. A major part of the permitting efficiency is attributable to the fact that the mine is new and the permit application was prepared and reviewed under a stable regulatory framework where guidelines published by the regulatory authority provide detailed instructions and approved methods for conducting baseline studies, preparing mining and reclamation plans, and even organizing a permit-application document. These guidelines not only contribute to permitting efficiency but should also increase the probability of successful reclamation.

Even in this case study issues remain with regard to evaluation of hydrologic restoration. Due to infrequency of flow events it will be difficult to evaluate surface-water restoration within the bond-release period. Due to the time it will take for the groundwater system to achieve equilibrium it will also be difficult to evaluate groundwater restoration through conventional monitoring. Evaluation of surface-water and groundwater restoration will have to be based both on monitoring and on evaluation of the hydrologic restoration plan.

3.15 Case Study O

3.15.1 Focus

This case study focuses on groundwater restoration for a mine in an area where cumulative hydrologic impacts to an important river system are a major concern.

3.15.2 Description of Mine and Hydrologic Setting

This case study corresponds with Case Study J in the Soil and Overburden report (Walsh, 1985), CO-1 in the Vegetation report (Western Resource Development Corp., 1985), and E in the Wildlife report (Cedar Creek Associates, 1985).

This mine, located in the Yampa River Basin of Colorado, is a dragline operation with a production rate of about 4 million tons per year. Operations began in 1962, and the mine has expanded several times until it now covers some 6,700 acres, of which 4,000 will be disturbed.

The hydrologic impacts of coal mining in the Yampa River Basin have been the subject of numerous investigations by various agencies and corporations, including the EPA, USGS, OSM, State of Colorado and several mining companies. These studies have included data collection programs and analyses of site-specific as well as cumulative hydrologic impacts of the numerous mines in this area.

The cumulative hydrologic assessment of the effects of coal mining in the Yampa River Basin were most recently analyzed by the OSM (Kaman Tempo, 1982) and the USGS, in cooperation with the Mined Land Reclamation Division of the Colorado Department of Natural Resources (Parker and Norris, 1983). These CHIAs are described in Section 2.3.2.3.1. For this case study, the mine plan document and these CHIAs were reviewed to summarize the data and analytical techniques used to determine the site-specific groundwater restoration plans for this particular mine.

This mine area is drained by an intermittent tributary to a small, perennial stream that in turn is tributary to the Yampa River. All streams that will be directly affected by mining are ephemeral tributaries to these intermittent and perennial streams. The perennial streams in the area are classified as cold-water fisheries; the intermittent stream is a non-sport fishery.

The main coal seam being mined is about 4 feet thick. Up to 120 feet of overburden are removed and replaced during mining. The coal seam is overlain by about 73 feet of siltstone, shale and fine-grained sandstone. The coal seam and this 73-foot thick overburden sequence comprise an aquifer that is confined in the vicinity of the mine. Above this aquifer is another thin coal bed (18 inches thick) that is also recovered, overlain in turn by shales continuing to the surface.

The mine is situated on the flank of a large syncline that trends northeast-southwest; the basin of the syncline is located to the northeast of the mine. The average dip of the coal seams and overburden strata in the vicinity of the mines is about 10 percent.

Groundwater recharge is thought to occur over the outcrop areas around the borders of the structural basin. From there, the groundwater moves through the mine area toward the center of the basin. Under premining conditions the groundwater was hydraulically isolated from the intermittent stream that drains the mine property. The discharge area for the groundwater moving through the permit area is hypothesized to be a perennial stream several miles to the northeast. This discharge is thought to occur upward through joints and fissures in the shales and comprises a substantial portion (25 percent) of the mean annual flow of that stream. The water quality of the aquifer is marginal for domestic use (TDS = 640 mg/l) but suitable for domestic and livestock use.

The regulatory agencies, in their environmental assessment of the mine, centered on two groundwater issues. These were: 1) recharge in the postmining environment and elevated dissolved-solids concentrations in the postmining groundwater, and 2) the potential for this spoil water to impact perennial streams in the area.

3.15.3 Presentation of the Case Study

3.15.3.1 Baseline Data

Due to the attention that mining in this area has received, stemming from concern over impacts to major perennial streams, a relatively large amount of hydrologic data were available for this area. Surface-water data included four years of data from two stream-gaging stations operated by the U.S. Department of Agriculture (1981), three USGS streamflow-gaging stations with records of four years each, and one long-term USGS station. The applicant maintains two streamflow gages on the intermittent stream and two on the ephemeral stream. There were no data available on flow or quality for the small ephemeral streams to be affected by mining (Kaman Tempo, 1982, p. C-5); all of the stations mentioned above are on intermittent or perennial streams in the vicinity. Available groundwater data included regional data from three USGS test wells constructed in 1976 and the operator's system of 47 test wells, of which ten are used as monitor wells. Four discharge sites are monitored by the applicant for discharge quantity and a limited group of water quality parameters.

Aquifer hydraulic parameters were determined from pump tests conducted by the operator and others. Data for a small (11 feet thick) sandstone layer above the upper coal seam were determined by the USGS from a drawdown test conducted in 1975. The operator conducted a long-term pump test of the main aquifer in 1977 using one pumping well and nine observation wells. Some of the observation wells were completed in the alluvium of the intermittent stream that flows through the property and results were used to document the fact that this stream is hydraulically isolated from the confined groundwater system. Two additional pump tests were performed in other areas of the property in 1980 and 1982.

The applicant used the data acquired from the installation and monitoring of the test wells to prepare geologic maps and cross sections and a potentiometric surface map, which were included in the application.

3.15.3.2 Analytical Techniques

In their Technical Analysis of this mine permit, dated February 22, 1980, the USGS identified five areas of concern regarding probable hydrologic consequences of this mine including:

a. dewatering of the overburden aquifer;

b. drawdown in adjacent areas;

c. increased recharge after mining compared with premining recharge;

d. leaching of soluble ions from the spoil material; and

e. transport of dissolved salts to off-site areas.

The methodology employed by the applicant to address these concerns is described below.

The initial boxcut was located at the deepest planned mining level, and mining occurs in an upslope direction from there. This exposes the overburden in the initial boxcut at a point where it is under 120 feet of static head.

The inflow of groundwater to the open pit was calculated using standard methods employing the Theis non-equilibrium equations (Lohman, 1972, p. 15). Inflow rates were determined at discrete time intervals representing the locations of the pit in one-year increments.

The calculated inflows were used to determine resultant drawdowns at selected distances from the pit using equations developed by Jacob and Lohman (in Lohman, 1972, p. 23) for point-sink, constant drawdown conditions. Drawdowns were determined for distances of 10, 100, 500, and 1,000 feet from the open pit and plotted on a map. The drawdown calculations were assumed to represent worst-case conditions since the analytical procedure ignored the existence of faults, the gradient of the potentiometric surface, and all drawdown calculations were based on the maximum computed inflow rate. Since the simulations represented "worst-case" conditions and no existing water users were predicted to be adversely impacted, the regulatory authorities considered the drawdown impact during mining to be acceptable.

Another regulatory concern was the effect of the mine on aquifer recharge. Prior to mining the area was underlain by several feet of shale that formed an effective confining layer over the 73-foot thick aquifer that consisted of the coal seam and the overlying sequence of siltstones and fine sandstones. This shale prevented recharge to the aquifer by infiltration of precipitation and downward percolation. After mining, the shale confining layer will be replaced with spoil which will have a higher permeability, permitting vertical recharge. The regulatory authorities were apparently concerned that the increase in recharge would exceed the rate at which the down-gradient face of the mine could remove the water, thereby creating saline seep areas in the spoils.

To address this concern the operator first estimated premining recharge to the aquifer by using a flow-net analysis (Walton, 1962). Data for this analysis included the operator's premining potentiometric surface map for determination of gradients, geologic maps for determination of fault locations and outcrop areas, aquifer hydraulic data from pump tests, and water-level fluctuation data from the operator's monitor wells. No data were available with which to determine recharge capacity of the spoils. This was simply estimated as 25 percent of annual precipitation (4 inches per year). The results of these calculations were sufficient to convince the regulatory authorities that all spoil waters could flow from the mine area, via undisturbed strata, toward premining discharge areas within the basin.

The concerns regarding postmining spoil-water quality were addressed by the operator through the use of column leaching studies. The operator had previously conducted geochemical analyses on 156 individual samples of overburden from 29 drill holes. Therefore, a good database existed for the selection of overburden samples for the leaching study. A total of seventeen overburden samples were collected from four holes spaced throughout the property at a density of about one hole per square mile of area to be mined (see Table 8). Maps were provided showing locations and elevations of each drill hole. Lithologic logs were provided, and stratigraphic cross sections through each of the four drill holes were prepared.

The overburden leaching columns were prepared using only the overburden fraction finer than 0.5 mm. The investigators stated that previous experience had indicated that this fraction represents 90 percent of all spoil fragments and contributes virtually all of the salts.

The 17 overburden samples were placed in 17 cylinders, 15 cm high and 3.81 cm in diameter, in quantities of 117 cubic centimeters.

Tap water was applied to the top of each cylinder so that a constant head of 1.0 cm was maintained. When the leachate began to flow out of the bottom of each cylinder, the instantaneous electrical conductivity and the cumulative weight of the leachate were measured at 30 or 60-minute intervals. When the readings were terminated the volume of the leachate exceeded the volume of the sample. The final, cumulative leachate from each column was analyzed for electrical conductivity (EC), TDS, pH, iron, manganese, sulfate, calcium, bicarbonate, magnesium, sodium, potassium, and chloride. Only electrical conductivity measurements were available for the incremental leachate samples from each column. Therefore, the ratio between TDS and EC was determined for each cumulative leachate sample, and this ratio was applied to each incremental EC reading to obtain a relationship between TDS and cumulative leachate volume for each column.

The column-leaching study was intended to provide a means to estimate postmining groundwater quality and the time that will be required for the spoil water to return to baseline water quality. To estimate the required time period, the relationship between TDS in the leachate and the ratio Ve/Vo, where Ve is the cumulative volume of leachate and Vo is the volume of the overburden material, was determined. This relationship was plotted, and from the resulting curve the value Ve/Vo at which the TDS concentration was equal to the baseline (premining) value of 641 mg/l was determined for each column. From these data, one composite curve was drawn using a weighting factor according to the stratigraphic thickness of each sample. The composite curve indicated that when the volume of water that percolates through the spoil attains a volume equal to about 29 percent of the volume of the spoil material, the TDS value will be at baseline level.

This volumetric ratio was also expressed in terms of time by applying a factor for rate of water infiltration into spoil and for quantity of overburden. This was determined from the following equation:

$$t = rh/i$$

where:

t = time in years

r = ratio of leachate volume to spoil volume

h = average height of spoil in feet

i = infiltration rate of water from precipitation into spoils in feet per year.

In this calculation, the recharge to the spoil from the undisturbed overburden was ignored since it is estimated to be only about one percent of the total recharge to the spoils.

Solution of the above equation for t when the ratio Ve/Vo is 0.29, infiltration is assumed to be 4 inches per year, and average spoil thickness is 85 feet resulted in an estimate that about 74 years would be required for the spoil water quality to return to the baseline TDS concentration.

The final regulatory concern regarding the spoils aquifer was the impact to offsite areas as the high-TDS water in the spoils rejoins the groundwater flow system. It was theorized that the spoil leachate would percolate downward to the base of the coal and then flow down-gradient to the backfilled mine base. There it would pool against the less permeable, undisturbed aquifer and provide recharge water to the aquifer. The operator addressed this concern in the following manner.

The leachate water from the spoils were assumed to enter the undisturbed aquifer and be diluted by less-saline natural groundwater. A "plume" of relatively saline water will then emanate from the mine area and travel down-gradient, becoming more diluted with distance from the mine area.

The analysis of the groundwater solute transport was performed using the equations and method of analysis developed for dispersion of a tracer dye through a saturated, porous medium. The premining potentiometric surface map was used to determine the direction of flow and the rate of flow was determined from the potentiometric gradient and aquifer transmissivity values available from pump-test data. The average concentration of baseline TDS (641 mg/l) was then subtracted from the predicted leachate TDS concentration (3,600 mg/l) to determine the initial point-source contribution of salt to the undisturbed aquifer.

The contributed concentration after 50 years of leachate movement was computed for several radial distances from the mine plan area using the two-dimensional solution of dispersion (Fried, 1975). The solution of this equation provides the solute concentration above the baseline level at a known distance from the mine plan area. Solute concentrations were computed for distances of 2,000, 4,000, 8,000 and 12,000 feet from the mine-permit area. Contour lines of equal solute concentration were then drawn through the plotted points to graphically display the salt plume after 50 years of solute transport.

Results showed that TDS levels were diluted back to baseline levels within 7,000 feet of the mine area. Therefore, the effects of salt transport will not be measurable at the aquifer discharge area.

The Technical Analysis concurred with the models used, the input data, and the results. The groundwater effects of this mine were therefore not included in the OSM's cumulative hydrologic impact assessment of coal mining in the Yampa River Basin (Kaman Tempo, 1982).

3.15.3.3 Monitoring and Reporting

The operator has committed to installing wells and to monitoring water quality and water levels in the spoils and in the undisturbed aquifer down-gradient from the mine area. Results of monitoring will be submitted to the regulatory authorities with the results of other mine site monitoring.

Presumably, information should be available to verify the assumptions and calculations described above when the operator submits the next renewal application.

3.15.3.4 Evaluation Criteria

The regulatory authorities, following their review of the data and analytical techniques described above, issued the permit and determined that this mine would not contribute to cumulative water-quality impacts on the Yampa River. The application states that information gained during the drilling, testing and monitoring of spoils wells will be used to "verify the projections made herein on hydraulic characteristics of the spoils aquifer."

3.15.4 Identification of Issues

Column-leaching studies were used to estimate the chemical characteristics of spoil water. These column-leaching studies indicate that initial spoil leachate will be as much as 10 times higher in TDS concentrations than the baseline groundwater. The TDS concentration is expected to decline as additional water leaches through the spoils, reaching baseline after more than 70 years according to calculations presented in the application.

The applicant is required to monitor the spoil water quality, but there are no criteria against which to compare the results of the monitoring. Monitoring may permit verification of the assumption that water quality will trend toward baseline, and may even provide information with which to project when this will occur. However, monitoring cannot be expected to continue until baseline values are achieved. The time required to achieve baseline water quality is based on continual leaching of the spoils. This will not begin until mining ceases and the final pit is closed, permitting groundwater levels to begin to equilibrate with the postmining system. Therefore, monitoring of the spoil water may not be representative of postmining conditions until well after mining ceases. The regulatory agencies determined, based on the applicant's data, that there were no toxic or acid-forming materials in the overburden, and therefore no special handling of overburden during mining was required. There is little, therefore, that can be done if the monitoring indicates the spoil water quality is worse than anticipated. While not stated, it appears that the monitoring of spoil-water quality is intended more to provide information for future mining than to evaluate reclamation at this particular mine.

A key factor in the minds of the reviewing authorities was the spoil recharge rate. However, several calculations presented in the application are based on an unsupported assumption that recharge from surface infiltration would be 25 percent of mean annual precipitation, or 4 inches per year. There is no description of how monitoring will provide information to verify or refute this figure.

3.16 Case Study P

3.16.1 Focus

This case study examines the data and analytical techniques used to predict water quality impacts of burial of power-plant wastes in mine spoils. The case study focuses on how potential impacts to groundwater quality from the burial of these utility wastes were determined, how the proposal for waste disposal was evaluated by the regulatory authority, and how adverse hydrologic impacts will be mitigated.

3.16.2 Description of the Mine and Hydrologic Setting

The mine is located in the Yampa River Basin of Colorado on the north-facing slope of a mountain ridge which trends generally east-west at elevations between 6,400 and 7,700 feet. The mine is located on a near dip-slope, with the strata dipping slightly more than the slope of the topography.

Drainages within the permit area are all ephemeral channels that run south to north toward the Yampa River and north to south toward the Williams Fork River. The average annual precipitation of the area is about 13.4 inches, of which over one-third occurs as snow.

The permit area covers about 10,000 acres. Mining operations began in 1977, and about 2,500 acres had been disturbed by 1981.

Coal is mined using area strip-mining methods with a dragline used for overburden removal. Mining occurs in strips parallel to the downhill dip of the coal seam, each pit being adjacent and parallel to the previous one. When more than one coal seam is recovered in a pit the partings are removed by shovel, dozer, or backhoe, if thin, or by dragline, if thick. The applicant has assumed a swell factor of 25 percent, which will leave the topography of the reclaimed surface an average of about 12 feet higher than the original surface.

Groundwater exists in bedrock and alluvial aquifers in the vicinity of the mine. The potentiometric head in water-bearing strata in the mine area decreases with depth, indicating the potential for recharge to lower strata from stratigraphically higher units. Down-slope from the mine area, the overburden, interburden and underburden contain highly confined artesian aquifers with sufficient head to flow at the surface. A sandstone unit in the overburden is a regional aquifer. The water quality of the sandstone is categorized as poor for domestic use and good for irrigation and livestock use with TDS concentrations between 600 and 1,000 mg/l (see Table 1). Sulfate, iron and TDS concentrations are consistently in excess of recommended drinking water standards. The sandstone unit, prior to mining, recharged at its outcrop within the mine area and discharged at its subcrop beneath the Yampa River. The aquifer will be removed in the northern limits of the mine, and at the end of mining the exposed portion of this aquifer at the northern pit face will be in direct contact with the spoils. If contamination occurs, water from the mine area could enter this aquifer and seven bedrock wells and two alluvial wells might be affected.

The mine backfill is used to dispose of utility-plant waste materials, including fly ash, bottom ash, and scrubber sludge. A maximum of 1,507 tons per day of the waste is placed in the mined-out pits, with an average of 1,221 tons per day. The waste is 60 percent fly ash, 20 percent bottom ash, and 20 percent scrubber sludge. The waste has a unit weight of about 0.8 tons per cubic yard, indicating that about 222 acre-feet per year of waste material will be placed into the backfill for a period of about 30 years. This waste material may be placed on the pit bottom, in the valleys between spoil ridges, and on dragline ridges.

3.16.3 Presentation of the Case Study

3.16.3.1 Baseline Data

Column-leaching studies very similar to those described elsewhere in this report were used to determine whether contaminants in the waste material are subject to dissolution and transport by contacting groundwater. It was determined from the data collected from the column-leach studies that water percolating through the waste could produce leachate concentrations of aluminum, barium, chromium, sulfate, boron, and molybdenum in excess of EPA primary and proposed secondary drinking water standards and recommended limits for irrigation water. With the exception of sulfate, the concentrations of these contaminants are reduced through attenuation mechanisms within the spoil material.

Following review of the column-leaching studies the regulatory authority stipulated that the waste material be buried above the projected postmining water table. Certain areas of the pit were designated as unsuitable for utility-waste disposal. The disposal plan delineates the highest postmining water-table elevation that could occur in the pit. Because the base of the pit has a relatively steep slope, this elevation is controlled by a spill point on the down-gradient end of the pit. No ash disposal is permitted below an elevation ten feet above the spill point. According to the regulatory authority, the disposal plan was sufficient to insure that there would be only one source of water that could contact the ash and transport contaminants down into the saturated zone; infiltration and deep percolation of precipitation. As described elsewhere in this report, recharge from surface sources is not well understood and not easy to quantify. The following section describes analytical techniques used by the operator to quantify recharge and support the contention that surface recharge would not transport contaminants from the buried utility wastes into the saturated zone.

3.16.3.2 Analytical Techniques

A monthly water balance for the upper four feet of soil was computed to determine the potential for surface recharge within the spoil zone where utility wastes would be buried. Data inputs for the water-balance calculation included precipitation, potential evapotranspiration, surface runoff coefficients, infiltration capacity of the surface soils, and moisture-storage capacity in the top four feet of soil. For each month, the amount of precipitation in excess of runoff was calculated and assumed to be available for infiltration. If this amount was less than or equal to the infiltration capacity, it became available for either storage in the soil (during winter months) or evaporation (during summer months). In successive months the soil moisture storage was incrementally increased or decreased depending upon whether infiltration and accumulated soil-moisture storage exceeded the evapotranspiration rate or vice versa. Water was available for downward percolation in any month when the accumulated moisture in the upper four feet of soil exceeded the storage capacity of the soil.

For the monthly water balance, records were available from which to determine monthly precipitation values. Infiltration rates were determined using double-ring infiltrometer tests. Surface runoff coefficients ranging from 0 to 0.25 were estimated. Potential evapotranspiration rates were calculated using well-established procedures, and soil moisture-holding capacities were predicted from textural analyses of the soil types.

The operator's analysis determined that, during a typical year, no deep percolation through the spoils from precipitation infiltration will occur. During very wet years, infiltration will exceed the soil-moisture storage capacity and thus provide a potential for infiltrating water to percolate below the 4-foot zone in which evapotranspiration was assumed to occur. Using the previous thirty-five years of weather data to estimate the probability of occurrence of deep percolation, the applicant determined that the average percolation rate is approximately 1.6 cm per year (0.63 inch, or about four percent of mean annual precipitation). Under these conditions, the applicant concluded that from 500 to 1,000 years would be required for the percolating water to reach the saturated zone. The applicant further theorized that very little of the percolating water would contact the spoils because the water would flow down the path of least resistance. In this case, the spoil material, which is 10 to 100 times more permeable than the waste material, would provide a path for percolating water.

3.16.3.3 Monitoring and Reporting

The applicant has several water-quality monitoring wells located both up-gradient and down-gradient from the ash disposal site. Locations of wells and constituents to be analyzed should be sufficient to detect groundwater quality impacts from ash disposal should any occur during the monitoring period.

3.16.3.4 Evaluation Criteria

The regulatory authorities reviewed the applicant's plans for utility-waste disposal and determined that a potential existed for groundwater-quality degradation. The authorities attempted to minimize this potential by specifying zones in the spoil where utility waste would not be permitted. After evaluation of the potential recharge study described above, the regulatory authorities took issue with some of the conclusions. For example, the applicant's contention that downward-percolating water would preferentially flow through the spoils rather than the waste material was challenged. The regulatory reviewers noted that under unsaturated flow conditions, such as would occur here, finer-grained materials tend to extract moisture from adjacent, coarser-grained materials due to capillary action. The regulatory authority also stated that while the monthly water-balance calculation used to determine recharge may be correct, on an event basis there may be several times during the year when soil moisture exceeds storage capacity and excess water is available for downward percolation.

Following this evaluation, the regulatory authority attached conditions to the mine permit to further mitigate potential impacts of ash burial by requiring that ash disposal be done only in certain, specified pit locations where little groundwater has been encountered.

Based on the operator's plans and the regulatory agency's permit conditions, the OSM, in their CHIA of the area (Kaman Tempo, 1982), considered that the influence of the ash burial on spoil water quality at this mine is negligible.

3.16.4 Identification of Issues

The applicant used a monthly water-balance procedure to predict recharge to the spoil aquifer from infiltration of precipitation. Of the parameters used in this calculation, only one, precipitation, was obtained from actual data. Runoff coefficients, evapotranspiration, and soil-moisture storage capacity were estimated or computed from other data. Infiltration rates were estimated from double-ring infiltrometer tests, a method no longer recommended unless the water is applied by a sprinkling technique rather than flooding (Linsley and others, 1958, p. 167).

The postmining recharge rate, while estimated by the applicant to be two orders of magnitude greater than premining recharge from surface infiltration, was calculated to be very small (1.6 cm/year). This is about four percent of mean annual precipitation. By contrast, the previous case study illustrated impact analyses performed at a nearby mine based on an estimated recharge rate of twenty-five percent of mean annual precipitation.

This case study illustrates how little is really known about surface recharge. A great deal of variability is possible even when accepted techniques are used to estimate this quantity.

3.17 Case Study Q

3.17.1 Focus

This case study examines an experimental practice which consists of construction of a spoil fill area within a surface drainage. The applicant's plans for reestablishment of the surface drainage in the overburden fill are described. In the opinion of the applicant, the proposed method of excess spoil disposal provides an opportunity to advance technologies of mine-fill construction beyond the stringent existing design criteria and to assist in the formulation of a systematic approach to tailor design standards found in surface-mining regulations to specific conditions in the arid West. The operator maintains that the proven effectiveness of the practice will result in economic savings not only to the operator, but ultimately to the consumer.

3.17.2 Description of Mine and Hydrologic Setting

The study coal mine is located in Colorado and has been producing since 1977. Coal is produced at approximately 3.5 million tons per year at the present time, with a production goal of 4.5 million tons per year. Eight seams are mined, the upper three by truck/shovel and the lower five in a dragline operation. All of the coal to be mined during the life-of-mine is Federal.

The mine is located in a gently-sloping upland area. Land use in the permit and adjacent area is primarily rangeland and wildlife habitat. There is some dryland farming on level uplands, and there are small areas of irrigated pasture and hayland along stream courses in the general area.

Incised valleys in the area are generally narrow, V-shaped, and about 250 to 500 feet deep, with valley wall gradients of 40 to 100 percent. North of the mine site, the topographic surface is dominated by two ridges about two miles long, trending north-northeast. Mean annual precipitation is 18 inches.

Bedrock groundwater occurs in isolated, perched aquifers in the interbedded and lenticular sandstones and coals. Base flow in the two perennial streams in the general area is mainly groundwater discharge from alluvial aquifers in the stream valleys. Stratigraphically, the first major regional aquifer in the area is approximately 800 feet beneath the lowest coal seam to be mined. The principal recharge area for the aquifer is to the south of the permit area.

The surface-water hydrology of the general area is characteristic of a high altitude, semi-arid environment. Runoff occurs predominantly in response to rapid snowmelt and heavy rainstorms. The quantity and quality of the surface water reflects limited precipitation, high evapotranspiration rates, and the predominance of sandstones, shale and coals in the basin.

Several ephemeral drainages occur within the permit area, including the drainage being filled with spoil. The ephemeral streams drain to two perennial streams downstream of the permit area. The lower portion of the experimental drainage has been relocated as a result of an excess overburden fill at the mouth of the canyon.

In 1979, the applicant applied for a permit to engage in an experimental practice for the construction of a spoil-fill area within the permit boundaries. Reclamation at the mine has been limited to this excess overburden fill, over half of which had been revegetated by 1979. The initial mining operations began in 1976 along the southern face of the gulch. Box-cut overburden material was placed in the fill, which will, when completed, contain approximately 54 million cubic yards of overburden. The regulatory authority determined that spoil from the initial box cut is not required to achieve approximate original contours within the area where overburden has been and will be removed.

Detailed geotechnical work has been performed on the the fill to evaluate stability. Slope analyses were conducted for four water-table configurations within the spoil pile and for several different values for internal-friction angle and spoil density. The results of the study indicated that the slope is probably stable under dry conditions, but failures may occur should a high water table develop within the pile. Earthquake loading was not considered in the stability analyses. The fill will be constructed to blend in with the existing topography, and the average slope of the face of the fill will be approximately 3:1 (horizontal to vertical). The face will be topsoiled and revegetated. Mulching and contour furrows in conjunction with benches have been utilized for erosion control on the area of the fill that has been completed.

The fill consists of the initial fill placed in the gulch at the commencement of mining and the subsequent fill placed in the mined area as mining progressed in a southerly direction. Drainage from the face of the fill is collected in contour ditches adjacent to berms located at intervals of 100 feet in vertical height. The ditches are gradually sloped in the direction of a permanent channel located along the north abutment. The permanent channel empties into a sedimentation pond. No surface-water runoff will be directed over the face of the fill.

The drainage area of the fill contributing to the sedimentation pond will increase gradually as the area is mined and the fill is placed. The gradual increase of the drainage area flowing into the sedimentation pond allows time for reclamation of the landfill so that the fill placed in the early part of the operation is well vegetated by the time new fill is added to the drainage area. The application states that at any one time, only a small percentage of the total fill is new and therefore subject to erosion in the event of a severe rainstorm.

The restored channel was reportedly designed to pass the 100-year runoff event based on the maximum ultimate drainage area. Calculated velocity of flow for the 100-year runoff event is six feet per second. As this velocity was considered erosive by the applicant, the entire length of the channel will be lined with riprap.

3.17.3 Presentation of Case Study

3.17.3.1 Baseline Data

Baseline data collected by the applicant pertinent to the focus of this case study included:

1. groundwater-level data to show that the fill area is above the local water table,
2. drainage-basin data necessary to compute rainfall-runoff that will accrue to the permanent channel, including drainage area, relief, hydraulic length, and runoff curve number, and
3. Published precipitation frequency-duration data to compute rainfall runoff.

3.17.3.2 Analytical Techniques

The peak flow and runoff volume estimates were determined using the SCS triangular hydrograph method (see Section 2.3.2.1). The procedure was performed by hand calculation. No specific reference could be found on the specific form of the triangular hydrograph method that was used or the type of precipitation distribution that was used. The sediment pond at the base of the fill was sized to contain the runoff from the 10-year, 24-hour precipitation event. There was no justification of the runoff curve number used other than the statement that the soils maps were used in the determination. The method used to determine required sediment storage was also not described in the application.

The Manning's equation was used in the design of the channel and to check the velocity of flow in the channel for the design flood. This equation is an empirically derived equation that has standard applications in many hydraulic problems.

3.17.3.3 Monitoring and Reporting

The applicant plans to install and maintain a monitoring system assuring collection of data and the ability to identify potential risks to the environment and public safety. A well will be drilled and a piezometer installed to measure water presence in the spoil. Two survey monuments will be placed on each of the terraces, and control points will be placed on undisturbed areas adjacent to the fill to provide for measurement of vertical and horizontal movement of the fill. No discussion of monitoring of the restored channel is included in the permit application.

3.17.3.4 Evaluation Criteria

No evaluation criteria to assess the success of reclamation of the channel could be found in the permit application. The success of reclamation of the fill is based solely upon static slope stability analyses and a monitoring program for the detection of water in the spoils. No discussion was found in the permit detailing what the consequences of finding water in the piezometer would be.

3.17.4 Identification of Issues

The applicant has been permitted to proceed with an experimental practice whereby spoil material is deposited in a gulch. The original stream channel has been relocated along the north abutment of the fill. The studies conducted to date have almost exclusively been to evaluate the static slope stability of the spoils.

The design flood was determined using a runoff curve number that was not documented in the permit application. The curve number is a sensitive variable, and a small change can produce a large change in the peak runoff. The restored stream channel is completely lined with riprap due to potentially erosive velocities. Some states do not allow the use of engineered structures (i.e. riprap) for permanent channels because they may require maintenance. There is a question of long-term erosional stability of the channel and, therefore, for the entire spoil pile.

As was evidenced by the brevity of the data section, little hydrological information was presented concerning the spoil pile. No evaluation criteria were presented with which to determine the success of reclamation of the channel.

The intent of the experimental practice provision in SMCRA is apparently being ignored. Although called an experimental practice, it is not clear what hypothesis is being tested and there are no monitoring requirements or evaluation criteria other than those related to static slope stability.

3.18 Case Study R

3.18.1 Focus

This case study examines surface- and groundwater restoration in an arid area. The surface-water portion evaluates the design of a permanent diversion. For the groundwater portion, the analytical techniques used to determine the impacts on groundwater from disposal of power-plant wastes in the backfill are evaluated. In addition, the techniques used to predict the reestablishment of the potentiometric surface are analyzed. This mine corresponds with Case Study L in the Soil and Overburden report (Walsh, 1985).

3.18.2 Description of Mine and Hydrologic Setting

The permit area contains about 8,000 acres, of which about 4,400 and 3,600 acres are Federal and private surface, respectively. Approximately 6,800 acres of Federal coal are contained in the permit area. Both truck-shovel and dragline mining methods will be used to yield a production rate decreasing from a peak of 4.4 million tons per year to 1.0 million tons per year. The mine has been under operation since 1973 and supplies coal to an adjacent power plant.

The climate of the area is arid, averaging about 7 inches of precipitation annually. About one-half of the annual precipitation falls during July through October. The average monthly temperature ranges from a low of about 28 degrees Fahrenheit in January to a high of about 76 degrees Fahrenheit in July.

The mine is located on the western flank of a topographic and structural basin. The area is a dissected plateau which slopes gently west. The permit area is characterized by low mesas, buttes, and broad valleys.

The mine is drained by two arroyos, which are ephemeral above the lease area and intermittent below the lease area. These arroyos drain into a perennial river approximately 0.75 mile south of the lease area. The major arroyo draining the permit area is diverted around the mine. This diversion is permanent and was sized for the peak runoff from the 25-year, 24-hour precipitation event. The diversion channel was designed to conform to State of New Mexico, Surface Coal Mining Regulations (NMSCMC Rule 80-1) for permanent diversions and "Rules and Regulations Governing the Appropriation and Use of the Surface Waters of the State of New Mexico."

The second part of this case study deals with the hydrologic impacts of power-plant waste disposal in the backfill. Waste disposal includes the burial of fly ash, bottom ash, and centrifuge sludge from the power plant throughout the excavated portion of the mine area. A total of about 64 million cubic yards of power-plant waste will be disposed of in the backfill over the life of the mine.

3.18.3 Presentation of Case Study

3.18.3.1 Baseline Data

Monitoring of surface water started in 1974 at ten locations in and around the mine. Six of these sites are operated and maintained by the USGS. Three of the USGS sites have since been discontinued. Water-quality data have been collected by either grab sampling or single-stage samplers. No data from the monitoring program were included in the application. USGS data from the two stations along the main channel were used to show that the arroyo being diverted is an ephemeral stream.

Several tasks were performed to collect field data for use in design of the diversion. Sampling was done to obtain particle-size data for sediments in the arroyo, and the bottom of the arroyo was field-checked to locate bedrock outcrops. Surveyed cross sections were taken at nine locations to determine bankfull capacity. The design of the diversion required the development of a series of design hydrographs. Since adequate stream-gage data is not available for the drainages in question, all arroyo flows developed are based on rainfall-runoff relationships using the SCS triangular hydrograph technique.

Site-specific watershed data necessary for use of this technique were obtained from published literature and field evaluation.

3.18.3.2 Analytical Techniques

Watershed characteristics and precipitation-frequency data were used in conjunction with a mathematical model (SCS triangular hydrograph) to arrive at runoff volumes, peak flows and runoff hydrographs for various precipitation events.

A sediment-transport analysis was done to ensure that the hydraulic capacity of the diversion would not be diminished by sediment deposition during the design flow. The diversion channel was then sized to provide a sediment transport capacity approximately three percent greater than the sediment discharge of the arroyo. Sediment yield to the channel was estimated using the Universal Soil Loss Equation and a delivery ratio developed for the State of New Mexico. The method used to proportion the sediment transport capacity was not described.

When the diversion was originally permitted it was designed to carry the peak flow from a 100-year 24-hour storm event. In the spring of 1981 MMD and OSM concluded that the design of the diversion should include criteria which would allow the permanent structure to equilibrate with the existing stream channels. In order to accomplish this objective, the channel was designed to:

1. Maintain existing channel gradients,
2. Maintain subcritical flows during the design event,
3. Maintain concentrations of suspended material throughout the diversion length by allowing for gradation processes,

4. Allow the structures to adjust to the existing hydrologic regime, and

5. Hold, at a minimum, the bankfull capacities of the undisturbed and receiving stream channels.

The applicant requested that the revised design be based on a 10-year 24-hour storm event. MMD and OSM rejected this idea because the existing channel capacity was well above the 10-year 24-hour peak discharge, and there is a high probability that a storm in excess of the 10-year storm will occur during the mine life. MMD and OSM stipulated that the diversion be constructed to safely pass the peak flow from a 25-year 24-hour flow event.

The diversion channel is lined with riprap for most of the length, and two riprap drop structures are provided in the diversion.

Based on a field inspection of the diversion, a Notice of Violation (NOV) was issued due to excessive erosion of the diversion on August 31, 1984. According to mine personnel, only one major flow had occurred in the diversion since construction was completed in 1983, and the maximum depth of flow was less than 3 feet. However, this flow was apparently responsible for cuts four to five feet deep in the east bank of the diversion. Erosion had affected a 150-foot to 200-foot long section of the diversion. It was the inspectors' belief that the present condition of this part of the structure was primarily due to two factors: 1) the east bank of this diversion was not riprapped, and 2) riprap was not placed along the entire bottom of the diversion as called for in the plans.

Following a hearing the NOV was vacated. The regulators gave the following reasons for their decision:

1. Hydrologic systems in the arid southwest in ephemeral streams are very dynamic and in a natural condition change in response to each major flow.
2. Given the natural background levels of suspended solids entering from above the permit area, the contribution from erosion of the channel within the permit area will be insignificant, in most instances. Through surveys of the longitudinal gradient following major events, it can be shown in a quantitative manner that equilibrium of volumes is reached.
3. It should also be noted the intent of the diversion is to divert flows around the disturbed areas. The mine is designed as a "zero discharge mine". No runoff from disturbed areas is to enter the diversion.
4. The applicant has committed verbally to survey the channel after major flows.
5. The applicant verbally recognized the need to monitor the lateral incision and potential cutting into disturbed areas.

As described in the following section a monitoring program has been developed to help evaluate the diversion.

The assessment of potential impacts to groundwater quality and potential receptors from mining and waste-disposal operations at the mine was conducted in two distinct, yet interdependent efforts. These two efforts are referred to as the laboratory and groundwater leachate transport studies. Laboratory studies were conducted to evaluate the potential chemical impact of spoil/waste materials on groundwater quality in the coal seam. The coal seam was selected as the stratum of principal study because it is the main water-bearing unit of concern with respect to water-quality impacts.

Laboratory studies for the evaluation of chemical impacts on groundwater quality in the coal seam included the sampling and analysis of power-plant ash wastes and groundwater and column-leaching studies using composite mine-spoil samples and a composite mixture of mine spoil and power-plant ash wastes to estimate the impact on groundwater quality as it flows through the reclaimed mine areas. Leachates derived from the composite leaching tests were exposed to coal samples from the coal seam in batch-mixing tests to determine the potential for attenuation of groundwater contaminants by the coal seam. Compaction and permeability tests were performed on the composite spoil and waste materials to assess the postmining hydraulic properties of the reclaimed mine areas.

The leaching studies were mathematically modeled using solute-transport equations. The following worst-case assumptions were used in this model:

- The contaminant/coal reactions are instantaneous and maintain local equilibrium.
- The exchange reactions of the waste constituents between coal and solution are reversible.
- The coal formation is a continuous homogeneous medium.
- The concentration of each chemical species is sufficiently low that each species reacts independently and does not affect macroscopic properties of the water.

Leachate travel to the river valley will not occur until water levels in the mined-out areas have recovered following the completion of mining. The shortest time of travel for leachate-affected groundwater to reach the perennial river valley near the southern mine boundary was estimated to be about 1600 years. Time of leachate travel from the northern mine area to the perennial river valley was estimated to be 9500 years.

After mining ends and the pits are backfilled and reclaimed, inflow to the reclaimed mine spoils will continue until an equilibrium is reached with the potentiometric surface of the coal seam. The potential sources of inflow water to the pit were identified as:

- Coal seam
- Alluvial fill at subcrops
- Infiltration from precipitation
- Vertical recharge from the underlying sandstone

Three simplifying assumptions were made in the estimation of the postmining water-table elevation. First, discharge to the reclaimed spoils from the alluvial aquifer will remain constant and is not affected by fluctuations in the alluvial water table. Second, flow through the mine spoil will be uniform throughout the disturbed area. Third, aquifer loss and infiltration into non-water bearing strata were assumed to be negligible.

The time of reestablishment of the water table in the backfill was estimated with a computer model that was developed for this study. The model is based on equations developed by McWhorter (1981) for steady-state confined flow to a line sink.

Based on the results of the model, the operator predicted that more than 300 years are required for the backfilled pits to reach hydrologic equilibrium. The long amount of time required is due primarily to the relatively impermeable nature of the recharge sources (i.e. the coal seam and the alluvium) and the size of the excavated area.

3.18.3.3 Monitoring and Reporting

The applicant was required to commit to a program of monitoring and surveying the longitudinal profile of the permanent diversion after major flows. This program is to be developed in consultation with The New Mexico Mine and Minerals Division (MMD) and OSM. MMD will consider a major flow to be any flow exceeding three feet in depth at any point within the diversion channel.

The applicant also committed to the development of a plan to monitor the lateral incision of the channel to assure that excessive erosion is prevented and stability of mining-disturbed areas is assured. OSM requested that this plan include, at least in general terms, a description of mitigation measures to be taken if incision becomes excessive and a definition of the maximum allowable lateral incisions. This plan is to be developed in close consultation with MMD and OSM and must be approved by MMD and OSM before May 1, 1985.

Groundwater monitoring is conducted annually on wells completed in the coal seams and the underlying sandstone wells. Quarterly sampling is done on the alluvial wells. There are 23 monitoring wells in all, but the application does not clearly state how many will be monitored.

All monitoring wells are pre-pumped 24 hours before sampling, to help ensure that a representative formation water sample is obtained. Water samples are preserved, shipped and analyzed in accordance with EPA guidelines (EPA, 1976). Reports are made to the MMD within 90 days following sample collection.

3.18.3.4 Evaluation Criteria

The design event for the permanent diversion was negotiated between the applicant and the State and Federal regulatory authorities. Under current Federal regulations (30CFR 816.43(c)(3)) the diversion would only have to be designed for a 10-year 6-hour event since it is on an ephemeral stream and therefore is a diversion of a "miscellaneous" flow. New Mexico regulations (20-43(b)) require that permanent diversions be designed for the 10-year 24-hour event, or larger as specified by the Director. Detailed studies were conducted to design the diversion. Through a monitoring program, the operator will evaluate the erosional stability of the diversion following runoff events, and presumably will take corrective measures when damage is noted.

It is evident from problems that have arisen concerning the design of the diversion that an improperly designed restored drainage system could be detrimental to reclamation. With the exception of this diversion, however, the restoration of the drainage system within the permit area was not addressed.

The applicant did extensive studies to determine how long it might take for the postmining potentiometric surface to stabilize and to assess the impacts of disposal of power-plant wastes in the backfill on groundwater quality. Model studies using estimated backfill aquifer characteristics determined that it may take in excess of 300 years for the postmining groundwater system to achieve equilibrium. Studies of the impacts on water quality by power plant waste disposal in the backfill showed that little impact is expected. This was attributed to poor quality of the premining groundwater and the attenuation of the waste leachate by contact with the coal seam. The applicant is required to monitor groundwater quality, although no criteria were provided against which to compare the monitoring results.

The resaturation of the backfill is anticipated to take in excess of 300 years. It is not stated how long the applicant is to monitor, but if the predictions are correct the monitoring period will certainly be very short with respect to the time to reach steady-state conditions in the backfill. Nothing was contained in the application that indicates that any of the predictive techniques will be verified as additional data become available.

3.18.4 Identification of Issues

With the exception of the design of a permanent diversion, the restoration of the surface-water system was not addressed. Reasons are not stated, but there seems to be a lack of regulatory emphasis on this aspect of reclamation in this state.

3.19 Case Study S

3.19.1 Focus

This case study examines the plans for reclamation of the surface-water and groundwater systems in relation to those for previously-permitted mines to determine how hydrologic restoration technologies are improving with time. This mine, located in New Mexico, is not currently permitted but could receive a permit as early as the summer of 1985. No particular hydrologic issues have been identified for this mine.

3.19.2 Description of Mine and Hydrologic Setting

The proposed mine is located on the western flank of a topographic and structural basin. The proposed permit area contains approximately 2,600 acres. The operation will utilize truck-shovel mining methods to yield an anticipated production rate varying from 1.5 to 4 million tons per year. The mine will supply coal to a nearby power plant.

The climate of the area is arid, averaging less than seven inches of precipitation per year. Usually about one-half of the annual precipitation falls during the period of July through October. The average monthly temperature ranges from a low of about 28 degrees Fahrenheit to a high of about 76 degrees Fahrenheit.

The mine and adjacent area are drained by one intermittent stream and several ephemeral arroyos which are part of a perennial river watershed. All have deeply incised stream channels. The intermittent stream is tributary to the perennial river about six miles south of the mine area.

The intermittent stream drains a large, oval-shaped watershed with a trellis drainage pattern developed by capture of streams in a series of strike valleys and wide playas. The watershed is characterized by pinyon-juniper vegetation and heavy-textured saline soils. The valley width generally decreases as the stream traverses the more resistant formations and increases to the north and south of the permit area where the valley crosses less-resistant shale formations.

The channel has incised 10 to 20 feet into the unconsolidated valley-fill deposits. The active channel is broad and flat with minor terracing.

All surface-water runoff from the undisturbed areas will be diverted around active mining operations and facilities into natural drainageways via small ditches designed to pass a 2-year 24-hour precipitation event. All surface-water runoff originating from the active mining area will either be contained within the mine workings or retained within the disturbed area by means of berms, thus preventing runoff from leaving the active mining areas and reaching the natural drainageways.

Erosion-control practices to be implemented by the operator include the use of contour furrowing, grading along the contour, mulching and revegetation. The operator intends to construct contour ditches throughout the entire reclaimed area. The design details of these furrows, including the spacing on different grades, must be approved by MMD before topdressing can be replaced on any area of regraded spoil. By using the contour ditches the operator states that runoff and subsequently erosion and sedimentation will be temporarily reduced below natural levels. The permit application states that this should not have a substantial adverse impact on local channel geomorphology or the hydrologic balance since sediment yields and erosion rates should eventually approach natural or background conditions as the reclaimed areas stabilize and equilibrate with the existing environment.

During mining operations six minor watersheds will be disturbed. All have drainage areas of less than one square mile. The application states that these drainages will be reconstructed to their approximate premining area and flow length during final regrading and backfilling operations. "Fairly uniform gradients" will be maintained throughout each drainage to minimize the potential for headcutting. The applicant has committed to comparing postmining valley-slope profiles to the premining valley-slope profiles for each drainage to ensure that the approximate premining condition has been achieved.

The mine and adjacent areas are underlain by the Pictured Cliffs Sandstone Formation, Fruitland Formation, and unconsolidated alluvial deposits in the valleys of the perennial river and the two major arroyos. The Pictured Cliffs Sandstone and the alluvium were identified as water-bearing zones in the eastern portion of the mine area during the first hydrologic drilling program.

The Pictured Cliffs Sandstone is nearly 200 feet thick in the mine and adjacent areas. The formation strikes generally east-west and dips to the south and southeast. The sandstone is a well-cemented marine sand and exhibits both primary and secondary permeability. Due to low permeabilities, it is questionable whether this formation can be defined as an aquifer.

The coal seams of the Fruitland Formation in the mine and adjacent areas do not have primary permeability but exhibit secondary permeability associated with a well-developed cleat system and extensive fracturing. The seams strike generally east-west and dip to the south and southeast toward the center of the structural basin. Areas of clinker or burned coal are intermittently present along the outcrops.

Unconsolidated alluvial deposits of the valleys within the mine and adjacent area are narrow and vary in thickness to a maximum of 40 feet.

3.19.3 Presentation of Case Study

3.19.3.1 Baseline Data

A field reconnaisance conducted by the applicant identified only four ephemeral streams large enough to have a defined active channel. Peak discharge rates for these channels were calculated for various recurrence-interval flood events (2-, 5-, 10-, 25-, and 50-year events) by the channel-geometry method developed by the USGS (Scott and Kunkler, 1976).

Water-quality monitoring is conducted by the USGS at two stations on the perennial river, one upstream and one downstream of the mine area, and by the operator at one station on an ephemeral stream within the mine area on a monthly basis when the streams are flowing. Samples are also collected on the other arroyos during runoff events.

Data from these stations were used to relate seasonal variation of water quality parameters to the source of the flowing water. Runoff resulting from large precipitation events was sampled by single-stage sediment samplers or grab samples. The results show large concentrations of TSS, ranging from 496,000 mg/l at high flows to less than 1000 mg/l at low flows.

Permeable water-bearing zones were identified during drilling. Three coal seams were identified as water-bearing zones over most of the property. Exploration data indicated that burned areas and up-dip portions of the seams were not water-bearing within the mine area.

While there are indications of water downstream of the mine and adjacent areas in the high, ancient terraces incised by the perennial river, no water was found in these terraces within the mine area.

Aquifer characteristics were determined by installing test wells in each of the water-bearing zones on the mine and adjacent areas. Aquifer tests were performed to gain information on the aquifer characteristics. Single borehole tests were performed by airlift pumping a known volume of water from the piezometer. After pumping, water levels were monitored over time until the static water level was achieved. Slug-injection tests were performed at wells where previous borehole tests indicated the permeability was low. A known volume of water or "slug" was instantaneously injected down the well bore to increase hydraulic head. Water-level decline was monitored over a period of time.

Drawdown-observation tests were performed where a pumping well, open to all water bearing zones, was placed in the center of four single-aquifer observation wells such that the maximum distance between them was less than 60 feet. Water levels during pumping and recovery were monitored at each of the observation wells.

A constant-head test was performed on a flowing artesian well. The constant-head test consisted of allowing the well to flow freely for a period of time and then shutting it in with a well head and monitoring the shut-in pressures over time.

The Pictured Cliffs Sandstone had a consistently low transmissivity and therefore the applicant believes it is questionable whether it can be classified as an aquifer.

Transmissivities and apparent permeabilities were determined by the applicant to be random over the mine area, and no spatial trends could be discerned. There seemed to be less variance in apparent permeability than in transmissivity, which suggested to the applicant that thickness was increasing the variability in transmissivities.

Water-level monitoring began immediately after piezometer installation. Potentiometric surface maps were developed from the monitoring data. Vertical potentiometric head differences for the coal seams and the Pictured Cliffs Sandstone were used by the applicant to locate recharge and discharge areas.

An increase in potentiometric head with increasing depth was found at sites in the alluvium of the perennial river and the two main ephemeral streams. Therefore, the central topographic highs of the mine area were determined to be a recharge area, with discharge occurring at subcrops in the perennial river and the two main streams. Vertical-flow gradients were observed and attributed by the applicant to vertical leakage between the coal seams through the interburden.

3.19.3.2 Analytical Techniques

Peak discharges in the streams were estimated by a channel-geometry method developed by the USGS (Scott and Kunkler, 1976).

A computer model was used to project flows to and from the backfilled spoil after the end of mining. The model was a BASIC-language program written by the applicant's consultant to solve basic groundwater equations (McWhorter, 1981) on a microcomputer. The permit application included a complete source-code listing and a list of program variables. The location of the water table in the spoil at times of interest was also computed.

Recharge rates to the spoil were assumed to be at a peak just after completion of backfilling. Recharge will come from the perennial river, and inflows were calculated to decrease as the spoil resaturates and the gradient between the river and the spoil decreases. Discharges from the spoil to the undisturbed coal seams were computed to increase as the water table rises. A state of dynamic equilibrium was assumed to ultimately be established where inflow and outflow are equal. Based on the model predictions, the applicant determined that gradients will not return to the premining condition for hundreds of years, and the perennial river alluvium will continue to recharge the spoil, rather than receive recharge from the coal units as is the current condition.

Recharge into the spoil through the three bedrock units exposed in the pit wall was modeled as a line sink with recharge. The model used is based on equations developed by McWhorter (1981) for steady-state confined flow to a line sink.

The basic line-sink equations were modified to include the effects of a constant-head boundary at given elevation and distance from the line sink and parallel to it. Vertical recharge due to precipitation and leakage into the spoil from the underlying bedrock were added to the spoil as yearly sums. Head in the spoil was then adjusted to account for these inputs. The adjusted head was used in subsequent flow computations. Discharge from the spoil to the downdip aquifers was modeled as a line sink at the lower edge of the pit.

Output from the analytical solution and of the various equations of flow are presented in the application in a table of total flow into the spoil, discharge from the spoil into the three bedrock units, and head in the spoil at each requested time step. Flow to and from the bedrock is also listed.

3.19.3.3 Monitoring and Reporting

Surface water will be monitored on a quarterly basis using automatic samplers and recorders installed at three locations. Flow rates in the perennial river will be monitored at USGS surface-water gaging stations. All surface-water samples will be analyzed for parameters required by MMD (Table 4) and will be preserved, shipped and analyzed according to EPA (1976) guidelines. Those parameters consistently found at insignificant levels will be recommended for deletion from the monitoring program.

A minimum of two of the restored drainages will be monitored. Monitoring will be initiated prior to any release of runoff from disturbed areas at the mine. A station downstream of mining operations will consist of a continuous water-level recorder and automatic stage sampler. Water samples will be collected on a monthly basis or whenever a flow event occurs of sufficient magnitude to allow a sample to be taken. Supplemental information compiled for each runoff event will include the type of event, the precipitation amount and duration, the time period and conditions since the previous flow event, and the stage at which the sample was taken.

An existing pond constructed on an ephemeral stream will be monitored for sediment yield. The pond will be surveyed for bottom elevation in cross sections both north-south and east-west. The amount of deposition which has occurred since construction will be determined by physical means.

Topographic surveys prior to construction of the pond by the Bureau of Land Management in 1956 will be examined and compared with present conditions to determine the amount of sedimentation since 1956. These records will be verified by augering in specific locations to check sediment depths.

On an annual basis, the pond will be re-surveyed along the same permanent cross-sections to note any changes in elevations resulting from the accumulation of sediment. Flow or discharge to the pond will also be monitored by staff gage observations.

The aggradation or degradation of stream channels and land surface will be measured with the use of erosion pins. Erosion pins are stakes driven into the ground at the point of examination in a transect. Each stake has a datum mark indicating the ground-surface elevation at time of installation. Each pin is measured periodically for changes in surface elevation. Compilation of this data will be used by the applicant to indicate whether a particular area is in an erosion or sedimentation cycle.

One hundred thirty-two erosion pins are proposed for the permit area. Twenty-six stations, randomly placed in the two main ephemeral stream channels, are planned. Each station consists of three erosion pins spaced 10 feet apart in a linear transect. Three additional stations are planned for three other ephemeral channels. These will be placed on the premining sites and respective reclaimed sites. All 29 stations will be used to measure and evaluate changes in geomorphology.

Four stations will be used to measure overland sheet erosion in an area where no defined channel exists. These stations consist of eight erosion pins set ten feet apart at 20° angles from center. Each station will measure changes in surface elevation as a result of overland flow in areas near the headwaters of three drainages. Following mining, erosion pins will be placed on the respective reclaimed sites to check postmining conditions.

Thirteen erosion pins will be placed randomly over the permit area. Each pin location will be correlated with soils, vegetation and terrain and will serve to give, in general, erosional/depositional information for each area.

Each erosion pin station will be checked and measured on a quarterly basis. All measurements will be compiled along with soils, precipitation and vegetative information. After one full year of data collection, a plot of the changes in surface elevation versus distance from the center of the channel will be constructed. Each subsequent measurement made at each station will then be plotted; the final product being indicative of either a depositional or erosional process. After sufficient measurements have been made the applicant will attempt to evaluate the data and predict whether channels can be expected to "fill in." On a very localized level, the applicant feels it will be possible to evaluate these data and thereby evaluate possible impacts from mining operations.

No monitoring of the Pictured Cliffs Sandstone is planned because the site-specific and regional data compiled by the applicant and presented in the application indicate that this is a poor aquifer with low-quality water. The Fruitland Formation contains saturated zones of coal and carbonaceous shale which will be excavated within the permit area during mining operations. Water in this strata in the vicinity of each pit will drain into the pit. Following the backfilling operation, groundwater will continue to flow from the formation into the backfilled mine spoils until the potentiometric surface equilibrates. The existing wells in the formation will be monitored on a quarterly basis for static water levels and semi-annually for chemical parameters.

The existing alluvial wells within the permit area will also be monitored on a quarterly basis for both static water levels and water quality. After the twentieth year of mining operations, three additional monitoring wells will be installed and completed along the highwall of the final pit. These wells are replacements for wells disturbed during mining and will serve to monitor groundwater during the final 15 years of mining activities.

3.19.3.4 Evaluation Criteria

The evaluation criteria for the success of reclamation is based upon a proposed surface water and erosion monitoring program. Both undisturbed and reclaimed drainages will be monitored for water quality in order to provide a comparison to help evaluate reclamation success.

Should impacts to the hydrologic balance become visible, the application states that they would be seen in changes in stream-channel geomorphology and erosion rates. In place of monitoring the chemical water quality of the ephemeral drainages, the applicant will evaluate current or natural erosion rate patterns so that impacts on the hydrologic balance as a result of surface mining activities can be characterized and minimized. This will be done by comparing premining erosion to active and postmining erosion and "evaluating the climatic and physiographic factors."

There was no discussion of how the groundwater monitoring program would be used to evaluate reclamation. It was calculated that reestablishment of groundwater levels in the spoil would take many years past the bond release time frame.

3.19.4 Identification of Issues

The mine in this case study is unpermitted at this time but expects to receive a permit in late summer 1985. Reclamation efforts, as detailed in the permit application package, are more specific than previously permitted mines on Federal leases in New Mexico. It is apparent that reclamation techniques are evolving with time.

The reclamation plan for the surface-water system at this mine is more detailed than that for other Federal lease coal mines in New Mexico. Although there was little discussion of the design of erosionally stable channels and drainage basins or of the hydraulics of channel and flood-plain design, the applicant presented a well-planned monitoring program designed specifically to help evaluate the success of reclamation of the reclaimed drainages. Rather than simply measuring water quantity and quality, the monitoring program will include: 1) an analysis of water quality with respect to the type of event that caused the flow, 2) a determination of channel aggradation and degradation by the use of erosion pins and a comparison of the data thus obtained with similar data to be collected for undisturbed areas, and 3) a sediment accumulation monitoring program in a permanent pond that will be used to evaluate postmining sediment production and yield. This is an example of the type of monitoring program that can be developed when the monitoring is designed to meet a specific program need.

3.20 Case Study T

3.20.1 Focus

This case study describes the surface and ground-water hydrology of a relatively small mine with no outstanding hydrologic features. The study illustrates how the size and lack of outstanding hydrologic features of the mine affect permitting efficiency and reclamation success. The use of the Universal Soil Loss Equation for a baseline erodibility study is also illustrated.

3.20.2 Description of Mine and Hydrologic Setting

This mine is an existing surface coal mine in New Mexico. The current production rate is approximately 200,000 tons per year with the coal being transported by truck to a nearby power plant.

To provide for continued operation and expansion of the mine, a permit application and a mining plan were submitted for two Federal leases to the north of the existing mine encompassing about 3,400 acres. Mining in the amendment area will be a continuation of surface mining activities at the existing mine with production averaging 500,000 tons per year.

The mine and amendment area lie within the San Juan Basin, which is in the Navajo physiographic section of the Colorado Plateau. The permit area is located on a gently sloping upland covered by older alluvial deposits and eolian deposits which have high infiltration rates and provide little runoff. These upland surfaces provide the most stable land form in the area. The badland topography of the Bisti Wilderness Area is located near the permit area. Relief within the permit area is very low (75 feet).

The area has a semi-arid, continental climate. The average annual temperature at the site is about 50 degrees Fahrenheit. The warmest month is July, with an average temperature of 74 degrees Fahrenheit; the coldest month is January, with an average temperature of about 32 degrees Fahrenheit. Precipitation in the mine area averages about seven inches per year. The majority of the precipitation occurs in the form of short-duration thunderstorms.

Surface waters in the area of the mine include several small internally drained areas and two unnamed, poorly defined ephemeral drainages. The permit area contains no lakes, ponds, springs, or perennial or intermittent streams.

Surface waters in the area of the mine vary widely in quantity and quality, both annually and seasonally. Natural runoff from the mine area is derived almost exclusively from snowmelt and short-duration high-intensity summer thunderstorms. The resultant flows exhibit marked differences in erosional tendencies and sediment movement from one runoff event to another.

The groundwater system within the permit area and adjacent area consists of two water-bearing units; a formation below the coal seam to be mined and alluvial fill along several stream channels. Groundwater has not been encountered in the formation being mined during drilling or mining.

3.20.3 Presentation of Case Study

3.20.3.1 Baseline Data

In 1979, a monitoring program was initiated by the applicant to measure baseline water levels and water quality in groundwaters that might be affected by the mine and nearby power plant. This program includes a network of seven wells in alluvial deposits and two wells in the formation underlying the coal seam to be mined. The inception of the monitoring program was prior to any mining on federal lease lands or power plant construction activities.

Following completion of the drilling of the monitor wells, each well was pumped for some period for aquifer development, and at least one (usually two) short aquifer tests were conducted. Pumping rates during the tests were very small, and apparent transmissivities ranged widely, but were also generally very small.

Groundwater was not encountered during drilling in the formation which contains the coal seams to be mined. No wells are known to tap the coal seams to be mined near the mine area except for several test wells installed by the USGS; permeability of this formation was estimated from reports of testing at other locations. No water-table map was prepared due to the lack of water.

The operator concluded that potential effects of mining on the water quality and quantity of the aquifer below mining operations will be negligible, due to the 60 feet of underburden separating the lowest coal seam to be mined and the aquifer. The shallowest significant water-bearing unit below the coal seams to be mined is not considered a usable aquifer in any case; stratigraphic data from recent drilling shows that all stock and domestic wells in the area are completed in a far more permeable unit located below this formation. Actual specific capacity has not been determined for any well near the site, but very low values are indicated by the fact that many hours were required for the water levels in two monitoring wells completed in the formation to recover after air-drilling was completed.

In the amendment area, virtually all of the surface is blanketed by unconsolidated sands which drilling records indicate are unsaturated. A sandstone aquifer underlies virtually all of the permit area below the formation described above. Descriptions of cuttings for the two monitoring wells completed in this formation indicate that the unit consists principally of fine-to medium-grained, light-to medium-gray quartz sandstone, with common dark accessory minerals and abundant clay cement. Geophysical logs of the two monitoring wells, of coal exploration holes, and of oil and gas tests indicate that the unit is very clayey and has little more porosity than the claystones of the overlying and underlying formations. Aquifer tests were attempted in both wells but it was not possible to pump at sufficiently low rates to provide useful data.

A survey was conducted during the permit application process to identify impacts to groundwater users within three miles of the mining operation. Valid water rights documented by the State of New Mexico were examined, and the applicant concluded that mining will not affect groundwater use because the affected aquifers are not currently being utilized.

Data from the seven wells completed in alluvial aquifers indicates that water quality is variable but generally poor. The alluvial groundwater exceeded the New Mexico groundwater standards for irrigation water in some or all of the monitor wells during the monitoring period. The water quality in the sandstone aquifer underlying the coal seams is also poor.

The amendment area is drained by two minor ephemeral drainageways. The drainages are poorly defined, with grassy bottoms and gently sloping sides. Surveyed cross-sections and photographs are presented in the permit application package. A map showing the baseline surface drainage patterns is also presented. In general, the watersheds and watercourses are not well defined, and the area contains several small internally-drained areas. The applicant stated that the peak flows developed for the premining conditions will not vary greatly from postmining conditions. Since stream-gage data were not available for the drainages in question, all arroyo flows developed are based on rainfall-runoff relationships.

The occurrence of surface water within the Amendment Area is confined to the ephemeral drainageways. Sampling stations for surface-water flows adjacent to the permit area are monitored by the USGS. Suspended-sediment concentrations in these channels were found to be occasionally very high. There are no surface-water quality analyses available for the ephemeral streams draining the amendment area.

Surface-water samples collected from streams adjacent to the permit area are typically quite high in TSS and TDS, often exceeding irrigation standards. Dominant cations are calcium and sodium, with sulfate being the dominant anion. No excessive heavy metal concentrations have been detected in surface-water samples.

There are no defined drainage channels that enter the amendment area from the adjacent areas. The mining and reclamation plans do not include the establishment of defined drainage channels passing through the amendment area. Consequently, surface water will not be discharged through defined channels that exit the area, and no provisions have been made for installing stage-discharge monitoring equipment to measure surface runoff from the areas adjacent to or within the permit area.

3.20.3.2 Analytical Techniques

No analytical techniques or special practices were used in defining the reclamation efforts for the groundwater system. This was due to the limited aquifer potential in the area and the poor quality of groundwater in the area. There are no wells in the permit area or adjacent areas that would be affected by mining operations.

The baseline surface-water hydrology description was based on several common analytical techniques. Since there were no recorded or historic streamflow data available, streamflows were estimated. The SCS unit hydrograph method was used to estimate flow at various recurrence intervals. Watershed characteristics and precipitation frequency data were used in conjunction with the unit hydrograph method to arrive at runoff volume, peak flows, and storm hydrographs for various frequency precipitation events.

The Universal Soil Loss Equation (USLE) was used for the erodibility study included in the surface-water baseline section of the permit application package. The U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS) has been instrumental in the development and calibration of the USLE. The procedures used in this study are presented in USDA-SCS, Technical Release No. 51, Rev. January, 1975, and further defined for New Mexico conditions in USDA-SCS, New Mexico Conservation Agronomy Technical Note No. 28, October 1975. Soil-loss values were determined for each significant soil series present in the area using the USLE. The operator was of the opinion that, since the surface soils are being salvaged, stockpiled, and replaced above the regraded overburden, postmining soil loss values will vary little from premining conditions.

The recharge potential from the reclaimed surface layer of unsaturated, unconsolidated sands was determined using a water-budget approach. A total of about one acre-foot of water per acre per year may be applied as supplemental irrigation water in the mining and reclamation process. Natural precipitation events supply less than one foot of moisture per year, on the average, so total water applied to the reclaimed lands will be less than two feet per year. Average pan evaporation for the mine area is on the order of five feet per year. The applicant concluded that evaporation, in combination with the influences of low precipitation, capillarity, and transpiration, should result in very little water available for percolation through the soil profile and recharge of the spoil aquifer.

3.20.3.3 Monitoring and Reporting

Within the amendment area, the applicant concluded that there is little reason to expect water to move from the pit or reclaimed spoil areas into any deeper formations. The operator does not believe that monitoring wells are appropriate for the amendment area.

Single-stage sediment samplers were originally planned for surface-water sample collection at two points. Prior to installation of the equipment, the two sections were surveyed and stage-discharge curves were developed using normal-flow equations. In both cases, it was found that storms in excess of the 100-year, 24-hour event would be required to achieve a flow depth of one foot in the channels. Since the peak flows are small and the flow depths are shallow, sampling equipment will not be installed.

It was stated that the small drainages on the amendment area are not compatible with standard monitoring equipment, so grab samples will be collected when flowing water is observed by personnel at the mine. Results of the analyses of the grab samples will be reported to the New Mexico Energy and Minerals Department, Mining and Minerals Division within 60 days following sample collection.

3.20.3.4 Evaluation Criteria

Because the premining groundwater system was determined to have no significance, no evaluation criteria were presented to assess the postmining groundwater system.

After the completion of mining operations, the drainageways in watersheds contained within the amendment area will be re-established to attempt to minimize any long-term adverse affects. The permit application stated that the quality and quantity of surface waters will be protected by a return of the disturbed lands to the approximate original contours. No evaluation criteria were discussed in the permit application package, however, to assess the success of reclamation of the surface-water system.

According to the applicant, mining activities should have little effect on the long-term geomorphic stability of the landscape.

Alluvial and eolian deposits in the area have high infiltration rates; hence, these areas produce little runoff. The applicant recognizes, however, that the ultimate stability of reclaimed areas may be dependent upon external conditions. Recent studies in northwestern New Mexico (Wells and Rose, 1981) conclude that in semiarid landscapes, the migration of gully incision or headcutting from adjacent areas can affect the stability of reclaimed areas even though they have been properly engineered and revegetated. Though the applicant stated an awareness of this situation, no method was proposed with which to evaluate postmining landscape stability.

3.20.4 Identification of Issues

The mine is a relatively small coal mine in New Mexico. A permit application was submitted to the New Mexico Mine and Minerals Division and the Office of Surface Mining to accommodate future plans to mine federal coal. It was determined that mining will have little or no effect on groundwater due to the limited aquifer potential and poor quality of water in aquifers below the coal seam. No monitoring of the backfill was proposed in the permit applications.

The permit application raised concern over offsite gully and headcut migration onto reclaimed lands within the surface-water drainage system. This is an important item and is often overlooked. No matter how well designed and constructed the reclaimed surface-water drainage system is, headcut migration into the area could easily destroy all the reclamation efforts. The applicant recognized that this problem may exist, but did not evaluate the potential for occurrence within the permit area.

Very little information was presented in the permit application regarding the design of the reclaimed surface-water drainage system. The premining surface-water system was defined by description and location on maps, but information was not available for the postmining system. No geomorphic data or drainage profiles were presented in the permit application package for either the pre- or postmining surface drainage system. An erodibility study using the Universal Soil Loss Equation was conducted for the baseline section, but no postmining erodibility study was included to aid in the assessment of the hydrologic impacts to the surface-water system.

The postmining drainage-channel designs were not presented or evaluated in the permit application package. It appears that a high level of uncertainty exists concerning the reclamation plan for the surface-water drainage system.

4.0 ANALYSIS

In this section an analysis of the availability of and utilization of hydrologic data and analytical techniques, based upon information presented in Chapters 2 and 3, is presented. Included is a discussion of remedies for data inadequacies in terms of current programs and suggestions for future programs and of strengths and weaknesses of analytical techniques. The section also includes a discussion of criteria used to evaluate the success or the probability of success of hydrologic restoration.

This section is divided into four major subsections: data (with respect to types, sources and adequacy), analytical techniques, the evolution of analytical techniques since the enactment of SMCRA, and the criteria for evaluation of the success of hydrologic restoration.

4.1 Analysis of Hydrologic Data: Types, Sources and Adequacy

4.1.1 Surface-Water Data

The previous two chapters have shown that large amounts of data on surface-water quantity and quality in the coal-mining regions of the western states are available. Although there are exceptions, two generalities can be made based on the information presented herein:

a) Streamflow data necessary for assessment of the cumulative impacts of mining on the major perennial streams of the west are generally obtained from published literature, primarily from the U.S. Geological Survey. From studies of the impacts of mining on the Tongue, Yampa and San Juan Rivers, described in Chapter 2, specific data needs have been identified, but in general the existing streamflow database was sufficient to prepare a reliable, verifiable model.

b) Streamflow quantity and quality data for ephemeral streams, the most common type of stream to be directly affected by mining, are generally lacking. While nearly every mine investigated has a monitoring program which includes data collection for ephemeral streams, reliable data are still scarce. This is due in part to the infrequent and sporadic flow characteristics of these streams, and to maintenance problems and lack of quality-control programs for data collection and reduction.

All mining companies have surface-water monitoring programs that will be in effect throughout their mining and reclamation programs. Therefore, there is a rapidly growing collection of surface-water data being submitted to regulatory agencies in quarterly, semi-annual and annual reports. Most of this database consists of streamflow quantity and quality data and NPDES discharge reports required for all point-source discharges.

A review of the case studies presented in Chapter 3 reveals a general lack of utilization of surface-water data collected under the approved monitoring programs of the various mines. Case studies described in Sections 3.1, 3.4, 3.5, 3.6, 3.7, 3.8, 3.13, and 3.14 all showed that surface-water monitoring programs had been implemented, but none of these case studies contained a specific description of how and whether the data obtained would be utilized in any analytical technique or to evaluate the success of surface-water restoration plans. At least one case study (see Section 3.13) showed evidence that surface-water monitoring is a perfunctory exercise. The data collected, reduced and submitted to the regulatory authority were reduced incorrectly, indicating a lack of utilization of the data for any specific purpose and a lack of critical review of the data by the operator and the regulatory authority.

In Wyoming, steps are being taken to correct the data problem on ephemeral streams. The state is now encouraging the mining companies to reduce the number of the ephemeral-stream monitoring stations and to intensify the monitoring at the remaining sites by installing "small watershed monitoring installations" (William Kearney, Chief Hydrologist, WDEQ, January 24, 1985, personal communication). Instrumentation for such an installation would be similar to that used in the alternative sediment-control program described in Chapter 3 (Case Study 3.9). Data from similar installations collected over a wide area would be useful in quantifying baseline surface-water quantity and quality with respect to causative factors such as land use, season, and precipitation, and thereby may provide data to help evaluate the success of surface-water restoration.

Analysis of the case studies presented in Chapter 3 shows that the most meaningful monitoring programs are developed when data needs are identified and the monitoring program is carefully designed to meet these needs. Case Study C (Section 3.3) shows how data are being collected to evaluate the success of restoration of wetlands. Case Study I (Section 3.9) illustrates a comprehensive data-collection and evaluation program to determine the success of an alternative sediment-control program developed under an experimental practice. Case Study J (Section 3.10) illustrates how data are collected and utilized to define the EHF of an AVF and to provide baseline data to design and evaluate the plans for the restoration of the EHF. Case Study S (Section 3.19) presents a comprehensive erosion-monitoring program to evaluate the success of surface-water restoration.

4.1.2 Groundwater Data

From the mine-permit applications examined in this investigation it is apparent that most groundwater data utilized in preparing these applications are derived from monitoring conducted by the mining companies. Relatively little data required for specific mine-site groundwater analyses are available from State or Federal agencies. Data that are part of the mining companies' on-going monitoring programs are submitted periodically to the regulatory agencies as required and thereby made available to the public. Whether by special inter-company agreements or by merely searching the files of the regulatory agencies, most mining companies also utilize groundwater data from adjacent mines. The major mining companies near Gillette, Wyoming are members of a unique, cooperative organization which annually assesses regional groundwater elevations and flow directions in aquifers affected by mining. In no other coal-mining area examined in this investigation is there a similar, cooperative agreement to compile and evaluate groundwater information on a regional basis.

Because groundwater monitoring at most mines is independently conducted, there exists considerable variation in the frequency, geographic extent and duration of monitoring, as well as the suitability of the data for analysis. At several mine sites in Montana, the mining companies have augmented their own monitoring and data analysis by sponsoring regional and site-specific studies conducted by various State and university-affiliated agencies (refer to Sections 3.5, 3.6, 3.7 and 3.8). Data and conclusions generated from these studies are considered state-of-the-art, and are widely referenced in western mine-permit application documents. At the Montana mine of Case Study 3.7, the volume of groundwater and other hydrologic data generated by the company's own monitoring and through studies sponsored by the company is so large as to compel the company to develop special data compilation and reporting techniques.

The states of this investigation have adopted guidelines, written regulations, or provide guidance through meetings with applicants to assist the mining companies in developing programs for the collection of groundwater data for hydrologic baseline investigations and impact analyses (see Table 4).. In spite of these measures there is commonly great variability in the scope of the monitoring programs conducted by mining companies even within a single state. This probably is due in part to the fact that there is little uniformity or consensus among investigators and regulatory authorities regarding the types of analytical techniques required in the groundwater investigations. It is also no doubt due to regional differences and proximity of the respective mines to important hydrologic features such as perennial stream systems. The reason that groundwater-monitoring programs in New Mexico (see Sections 3.18 and 3.19) and North Dakota (see Sections 3.2 and 3.4) are less comprehensive than most others may reflect the fact that important regional aquifers will not be affected in these areas. Groundwater monitoring in the Yampa and Tongue River Basins (see Sections 3.5, 3.8, 3.15, and 3.16), where cumulative impacts may affect streams which are important fisheries and water-supply sources, is much more comprehensive.

The growing use of digital models is helping to point out areas where groundwater data are inadequate (see Section 2.3.2.3.1, 2.4.2.1, Appendices A-C, and Section 3.12.). Identified deficiencies include: 1) spatial variations in aquifer hydraulics, 2) directional permeabilities, and 3) recharge rates. No specific cases were found, however, where groundwater monitoring programs were revised to collect the needed data and the operator was required to refine the model to improve the accuracy of the predicted impacts.

4.1.3 AVF Data

AVF investigations in general are the one area where site-specific streamflow data are collected, analyzed and utilized in a systematic procedure designed for a specific purpose. This is a result of specific regulations and guidelines which emphasize AVF issues. Data for this use are almost exclusively collected by the permit applicant.

Groundwater data collection is much more intensive, both spatially and temporally, in AVF areas. These data are collected to provide input to the hydrologic budget equation (see Section 2.5.1) and to help quantify essential hydrologic functions such as subirrigation, interaction between surface water and groundwater, and interaction between the alluvial system and bedrock aquifers (see Section 3.10).

Mines with a declared AVF in or adjacent to their permit area generally have surface-water and groundwater monitoring programs specifically designed to detect impacts to the AVF. Where the monitoring program has been designed to meet specific needs, the quality of the data obtained is usually quite good.

4.2 Analysis of Analytical Techniques With Respect to Data

4.2.1 Surface Water

With few exceptions the design of surface-water structures, such as sedimentation ponds, diversions, and restored stream channels, does not rely on streamflow quantity or quality data. Design procedures have been developed to use published regional flood-estimating techniques or rainfall-runoff estimating techniques (see Section 2.3.2). Both of these methods use data readily available or easily obtainable from published literature, topographic maps, or site investigations.

The primary use of surface-water data has been by regulatory agencies in preparing their cumulative hydrologic impact studies. These modeling efforts (refer to Section 2.3.2.3.1) have generally relied on streamflow data available from the U.S. Geological Survey. While each modeling study has pointed out specific areas where additional data would be useful, there generally were sufficient data to meet the primary goals of the investigators. A potential concern is that since the CHIAs are generally based on impacts to major streams, because of the fact that long-term streamflow data availability is concentrated on such streams, impacts to important tributaries to the main streams may be overlooked.

This investigation revealed that the techniques for surface-water restoration vary widely among the states. Much of this variation is due to regional differences in slope, relief, and stripping ratios. For example, in thick-overburden areas where approximate original contours are restored, design of restored channels is often based simply on restoration of premining channel slopes or cross sections. In thin-overburden areas more emphasis is being placed on quantitative geomorphology and drainage-basin design in addition to hydraulic design of channels and flood plains.

Aside from regional differences such as overburden thickness and premining topography, this investigation revealed other differences among the various states in their approaches to surface-water restoration. Several of these differences are apparent in the case studies of Chapter 3. In general, Wyoming and Montana require more rigorous plans and designs for restored surface drainages and more baseline data on basin and channel geometric properties on which to base these designs. This contrast is apparent in comparing Case Studies E (Section 3.5), M (Section 3.13) and N (Section 3.14), where designs of restored drainages were prepared using both geomorphic and hydraulic principles, with Case Studies A (Section 3.1), D (Section 3.4), Q (Section 3.17), and R (Section 3.18) where little or no design of restored surface-water systems was provided (with the exception of the permanent diversion described in Case Study R). SMCRA and the Federal regulations address channel reconstruction only in general terms. Specific performance standards address only "permanent diversions" (30CFR 816.43). Revisions to these regulations (September 26, 1983) contain more specific design standards for permanent diversions for perennial and intermittent streams, but treat ephemeral streams only as "miscellaneous flows" (30CFR 816.43C). A permanent diversion for miscellaneous flows need only be designed for a 10-year, 6-hour precipitation event according to these revised regulations. Since most channels affected by mining in the western states are ephemeral, reclamation meeting only the minimum requirements of OSM's revised rules (10-year 6-hour event) would clearly lead to unstable restored surface-drainage systems.

Technologies for sediment control are basically the same in each state studied herein. Most operators use some form of the SCS triangular hydrograph technique (refer to Table 9) to compute the 10-year 24-hour runoff volume and some form of the Universal Soil Loss Equation, together with an appropriate sediment-delivery ratio, to estimate sediment accumulation. The one exception is New Mexico, which is just beginning to develop a policy on design and construction of runoff- and sediment-control structures (New Mexico Mining and Minerals Division, 1985). Previously, New Mexico had no design standards for sediment control structures. Requirements for sediment control in New Mexico were very similar to the alternative sediment-control structures described in Chapter 3 (Case Study 3.9), except that no monitoring and no experimental-practice variance were required.

4.2.2 Groundwater

There are essentially no regulatory requirements or guidelines regarding selection of proper analytical techniques in groundwater data analysis. In the permit applications examined in this investigation the analytical techniques ranged from simple, manually-performed numerical solutions to sophisticated, digital computer models (see Section 2.4.2.1 and Table 6). Selection of the types of techniques in the permit applications seemed to be based primarily on the individual investigator's experience and expertise or the level of desired effort.

If there is any regard given to the suitability of the techniques for the particular hydrogeologic conditions, it is not described in the permit applications reviewed for Chapter 3 with the exception of Case Study E (Section 3.5). Also, in some cases, it is very difficult for the reviewer to determine the manner in which a technique is used, or even the type of technique used. Although in this latter situation the regulatory agency commonly issues a deficiency comment requesting explanatory information, the lack of clear justification for selecting an analytical technique and describing the manner in which the technique is applied is often unresolved. Of all the case studies reviewed for groundwater analytical techniques, only one (Case Study E, Section 3.5) provided all the information necessary to justify the analytical techniques used and to explain the limitations and possible sources of inaccuracies.

The relative sophistication of the techniques by which groundwater data are analyzed in mine-permit applications does not necessarily determine the accuracy of the results. Both sophisticated computer models and simple, numerical solutions can be and often are incorrectly applied. The most common source of error in the simple, numerical techniques, which generally have very specific and limited application, is selection of a technique not suited to the site-specific aquifer hydraulic or physical boundary conditions (see Table 6). In the digital computer models, which are normally capable of treating a wide range of aquifer hydraulic and boundary conditions, the common source of error is having to assume too many critical input values, and/or the incomplete calibration of the model. In most instances, the use of sophisticated models was not foreseen at the time of the development of the groundwater monitoring program, and much of the data to which the model is highly sensitive are not available from the monitoring and testing program.

It is difficult to analyze whether any analytical technique is more accurate than another without subsequent data collection to verify or refute the predicted results. While all case studies presented in Chapter 3 include groundwater monitoring programs, in no case was a specific monitoring plan proposed for the purpose of verifying results obtained with either a digital computer model or a manual computational technique.

4.2.3 Special Analytical Procedures for AVFs

In general, the analytical procedures for AVFs are similar to, but more intensively applied than, those used in non-AVF areas. In AVF areas monitoring and data collection occur in a more concentrated area and time frame and results are more rigorously reviewed by regulatory authorities due to statutory emphasis on AVFs. Monitoring programs for AVF areas are designed and carried out for very specific purposes (see Case Study J, Section 3.10 for example), and regulatory involvement typically occurs early in the investigation process so that specific concerns are identified and handled in a more efficient manner.

Hydrologic studies of AVF areas are unique in that by law they are required to specifically analyze the relationships between hydrologic conditions in surface and groundwaters and land use, soil characteristics and vegetative productivity. In addition, most mine-permit applications provide a thorough assessment of the geomorphic and erosional characteristics of the valley floor, if the valley floor will be physically disturbed. To assess the special relationships in AVF areas most permit applicants attempt to quantify the variables of the hydrologic budget of the valley floor. The analytical techniques by which this is accomplished are described in Section 2.5.2. Restoration of an AVF is the only instance where a hydrologic evaluation is truly integrated with other facets of reclamation.

The apprehension that surrounded the issue of potential mining impacts to alluvial valley floors has apparently diminished somewhat over the last few years in the minds of most regulators. The reason for this is that hydrologic studies, such as those for the Tongue River basin in Wyoming and Montana and the Yampa River basin in Colorado, have shown that the impacts from mining to major river basins will be small. Also, most mining companies must now plan to keep their operations away from alluvial valley floors where farming is practiced, or limit their disturbance of such areas, in order to comply with the requirement to prevent material damage to off-site AVFs.

The criteria for premining evaluation of the essential hydrologic functions of AVFs are generally standarized among the regulatory agencies of the western states (see Figure 2 and Table 4). These same criteria will also be applied after mining in evaluating the success of AVF reclamation. These criteria are based upon accepted engineering and hydrogeologic principles. Although no designated AVF has yet been mined and successfully reclaimed, several mine permits have been issued which include plans for mining through and restoring an AVF. In time, it is generally believed that some types of AVFs will be successfully mined and restored to their premining EHF (OSM, 1983). Similar to hydrologic restoration in non-AVF areas, however, it may in some instances be many years or decades after mining and reclamation are complete before the hydrologic success of reclamation in AVF areas can be entirely assessed. This is due to the time that may be required: 1) for water levels to recover to elevations that will support subirrigation, and 2) for runoff events to occur that will enable assessment of the design and construction of the restored channel and flood plain.

4.3 Evolution of Analytical Techniques Since 1977

4.3.1 Techniques for Design of Restored Surface-Drainage Systems

Review of mine plans in the course of this investigation has revealed an encouraging trend toward a comprehensive, multi-disciplinary approach to the design of restored surface-drainage systems. Operators are combining the concepts of quantitative geomorphology together with rainfall-runoff hydrology and detailed hydraulic analyses to develop a plan for the restoration of erosionally stable channels and watersheds. As is apparent from the case studies in Chapter 3, Wyoming and Montana are well ahead of the other states studied in this regard. The importance of this aspect of reclamation is becoming increasingly apparent as reclamation proceeds and problems in channel stability are beginning to appear (Kearney, 1985).

The principles of quantitative geomorphology (see Section 2.3.2.4) are not new, being based on concepts developed over the last 50 years (Horton, 1932; Strahler, 1952), but their application to mined-land reclamation is new. Considering that the performance-bond evaluation period is relatively short in comparison to the design events necessary for restored surface drainages, it is doubly important that the restoration plan be based on sound engineering and geologic principles.

The advent of computers and readily-available software for such applications such as rainfall-runoff computations and water-surface profile calculations have added to the operators' abilities to prepare and analyze site-specific channel properties. This increases the assurance that well-designed restored drainage systems will be erosionally stable.

There is a growing awareness that drainage basins are open systems, and as such are subject to the effects of events that can occur in off-site areas (refer to Case Study T, Section 3.20). Although restored channels may be erosionally stable for events that occur within the permit area, they may respond to headward erosion in tributaries downstream from the permit area should these tributaries undergo a base-level lowering. If headward erosion should encroach into a reclaimed area, the effects could be more severe on the unconsolidated spoils than they would have been on the premining drainage system. This concern has raised questions as to the definition of "proximity" in 30CFR 816.103(a)(4) (and corresponding state regulations), which states that, "Acid-forming or toxic-forming material shall not be buried or stored in proximity to a drainage course so as to cause or pose a threat of water pollution." Some regulators have attempted to quantify "proximity" as the depth of erosion that might be expected in a channel during one major "geomorphic cycle" (Lidstone, 1983). A study of the particular stream or area is required to define, under this criterion, what depth of burial is required in order to not be in "proximity" to a restored channel.

A mining company in the Hanna Basin of Wyoming offered to take a more positive step in this regard. Rosebud Coal Sales submitted a proposal to the regulatory authority to place a submerged rock check dam at the downstream terminus of each restored channel to prevent headcutting from advancing upstream and into their reclaimed area (Western Water Consultants, Inc., 1984). This innovative technique is based on proven methods for gully control (Heede, 1966), but was rejected by the regulatory authority because they do not consider "engineered structures" to be a viable reclamation technique for long-term stability due to maintenance requirements (William Kearney, Chief Hydrologist, Wyoming DEQ, personal communication, July 31, 1984). This company's concern over the burial of acid and toxic-forming overburden stems partly from the fact that the definition of "toxic and acid-forming" has no quantitative standards. It is a relative term. Material that is toxic to plants when placed in the root zone may not create an impact when placed in the postmining saturated zone (and vice-versa). Material that is acid-forming in one environment may not be when placed in a low-oxygen environment (refer to Case Study 3.13). Definitions of toxic and acid-forming materials should be made with respect to the ultimate disposition of the material in question.

4.3.2 Techniques for Design of Hydrologic-Control Structures and Sediment-Control Facilities

Techniques for the design of hydrologic-control structures and sediment-control facilities have changed very little since promulgation of final rules and regulations under SMCRA. There is an increasing use of computers in design, and there has been a gradual standardization of runoff- and sediment-estimating techniques toward the SCS triangular hydrograph technique and the Universal Soil Loss Equation, respectively. New Mexico is different from the other states in that a policy for design and performance standards is just now being developed (New Mexico Mining and Minerals Division, 1985).

On October 13, 1982 EPA issued final rules setting effluent limitations for coal mines (see Federal Register, Vol. 47, No. 198, 40CFR 434.40). Generally, these revised regulations eliminated specific design and construction standards for sediment ponds and imposed a far less stringent settleable-solids (SS) effluent standard to be used for sediment-pond discharges that occur during precipitation events and for reclaimed areas. The original total suspended solids (TSS) standards still apply to all discharges when no precipitation is occurring and to pit-water discharges. On September 26, 1983 the OSM revised its effluent-limitation rules to be consistent with the new EPA rules. Thus, under Federal regulations, sediment-pond design standards have been eliminated in favor of effluent standards that are less stringent than before. If the states revise their regulatory framework to incorporate these changes, undoubtedly the design procedures for sediment ponds will change as well. Currently, in order to assure compliance with effluent standards, sediment ponds are generally designed to fully store all the runoff predicted to occur from the 10-year 24-hour runoff event. The water may then be gradually released after being detained long enough to meet the TSS effluent standard. Because of this practice the cumulative effect of sediment control at several mines can be a significant loss of water to downstream users, as described in Section 2.3.2.3.2.

Case study 3.9 in Chapter 3 illustrates both innovative sediment-control practices and state-of-the-art sediment and runoff-monitoring techniques for ephemeral streams. As regulatory agencies become more comfortable with this approach it is possible that more mines may resort to alternative sediment control, with the result that water quality will be protected while creating smaller impacts on the availability of water for downstream users. This is a critical item in the semi-arid West.

As illustrated in Chapter 3 (Section 3.9), the use of alternative sediment control is apparently dependent upon the designation of any structures used as non-point discharge sources. If these structures are declared to be point sources, they become subject to effluent criteria as well as receiving-water quality standards. There is no strict regulatory distinction between sediment ponds and sediment check dams (John Wagner, Wyoming DEQ discharge permit supervisor, January 15, 1985, personal communication). However, discharges from a sediment pond must currently be less than 70 mg/l in TSS, while discharges from alternative control structures could have TSS concentrations in the tens of thousands and be in compliance with Wyoming regulatory program standards so long as the receiving water is not adversely affected. As explained in Section 3.9.4, uncertainty remains as to precisely how alternative sediment-control technologies will be evaluated. The OSM, in approving the experimental practice, indicates that the alternative sediment-control measures will be evaluated in terms of whether they are at least as effective as sediment ponds. If this means achieving point-source effluent standards, obviously alternative sediment-control practices will not be as effective as ponds. However, the evaluation program described in Section 3.9 is designed, with state concurrence, to prevent additions to naturally-occurring TSS concentrations. In addition to non-degradation of water quality, the alternative sediment-control practices described in Section 3.9 will also be evaluated in terms of minimizing land disturbance and changes to natural streamflow rates (see Section 3.9.3). If these additional criteria are also used to evaluate the performance of alternative sediment-control measures, then the alternative measures may be more effective than sediment ponds in some cases. Regarding sediment control, the definition of best practicable control technology may have to be changed to recognize other factors in addition to point-source performance standards.

4.3.3 Techniques For Prediction of Pit Inflows and Drawdowns

The development of quantitative methods for prediction of groundwater inflow into excavations has lagged behind other developments in groundwater science, and the effects of this lag are evident in review of mine-permit applications. Although digital computer models are now available for the accurate prediction of groundwater pit-inflow rates and drawdowns, they are not often used by mining companies. The permit applications reviewed for this investigation show a great diversity in the techniques used to estimate these parameters. State mining regulations and guidelines for suggested analytical techniques provide essentially no assistance for selecting the proper technique to predict groundwater inflow rates and drawdowns.

Most mine-permit applications for older mines generally utilize historic data or one or more basic groundwater equations to estimate potential groundwater pit-inflow rates and drawdowns (refer to Table 9, Case Studies B, D, F, and H). The assumptions inherent in equations used and rationale for suitability of the equations for the mine-site hydrogeologic conditions were usually not described. If basic assumptions are not met (see Table 6 and Section 2.4.2.1), the techniques are inappropriate and the results may be subject to considerable error. More recent permit applications (see Table 9, Case Studies E, J, N and S) show an evolution towards the use of more sophisticated pit-inflow rate and drawdown computational techniques which are individually developed by the investigator. Usually these techniques involve the repetitious solution of several standard groundwater equations suited to a particular aspect of the local hydrogeology or the pit progression. Many of these methods involve the use of small computers to improve speed and accuracy of the calculations. Relatively few mining companies utilize sophisticated state-of-the-art digital computer models, such as those available from the USGS or other public agency. This may be due to the expense or the lack of computer facilities and trained personnel to set up and run the model.

As described in Section 4.2.2, a common problem still existing in most mine-permit applications is the lack of justification for selection of a particular analytical technique, and description of the assumptions inherent in the technique and how these assumptions are satisfied by the particular situation. In many instances this lack of information renders the analysis essentially incomprehensible even to the experienced hydrologist.

4.3.4 Techniques For Restoring Aquifers in Mine Spoils

By virtue of recent research and analysis of data on hydrologic conditions in mine spoils, the level of knowledge on this subject has improved significantly since 1977. This is particularly true in regard to techniques for approximating some postmining groundwater-quality characteristics. Presently, however, researchers are divided in their opinions on the technique for the burial of toxic or acid-forming overburden in mine spoils that will best minimize impacts to groundwater systems. Methods for predicting postmining spoil hydraulic characteristics have not advanced significantly, and with the exception of the special handling and replacement of alluvial aquifers in AVF areas, no techniques are employed in most mine operations to ensure that spoils will adequately transmit groundwater flow. A notable exception to this, although not addressed in the case studies of Chapter 3, is the efforts of AMAX Coal Company to reconstruct an aquifer by selectively placing sandy overburden materials in the backfill at the Belle Ayr Mine near Gillette, Wyoming (Stowe, 1985).

Presently, the regulatory authorities of all western coal-mining states can require that toxic or acid-forming overburden or interburden materials be selectively buried in spoils in locations above the postmining water table and away from drainage channels. Several truck and shovel operations have committed to the special handling of these types of materials, presumably because of their mechanical ability to selectively strip even relatively thin strata. Mining companies with dragline operations generally commit to attempt to specially handle at least thick deposits of toxic or acid-forming materials; however, due to the mechanical limitations of a dragline operation it is doubtful that they are successful in these attempts. For either type of operation special overburden handling can be an economic burden. Until techniques to quantitatively predict spoil-water quality improve, it will remain difficult to evaluate the effectiveness of special overburden handling, and conflicts between operators and regulators may continue.

As described in Section 2.4.2.4, some researchers have determined that the environmentally best method for disposal of toxic or acid-forming spoils is to bury them below the predicted postmining groundwater table. The mine regulatory agency of Wyoming is currently allowing a test at a mine in that state (see Section 3.13) to determine if the simple mixing of chemically unsuitable spoils with suitable spoils might provide a means for adequate disposal of chemically unsuitable materials. Based upon the current state of experimentation and differences in theories regarding the proper disposal of toxic or acid-forming materials in mine spoils, it is apparent that the understanding of this subject is still in an evolutionary state. Special handling of overburden, where required, is ostensibly intended to minimize adverse impacts to the hydrologic balance. However, under current technology the spoil-water quality cannot be predicted with sufficient precision to quantify the difference in spoil-water quality with and without special handling so that the special handling can be quantitatively evaluated with respect to its impact on water quality.

The western states considered in this investigation are all concerned that burial of solid wastes from coal-fired power plant operations (ash and centrifuge sludges) might create adverse impacts to postmining water quality. A mine in Wyoming encapsulates its power-plant ash in compacted clay liners to minimize contact of the ash with groundwater in spoils (see Section 2.4.2.4). A mine in Colorado buries power plant fly ash and centrifuge sludge in dry mine spoils above the predicted postmining water table (see Case Study 3.16, Chapter 3). A mine in New Mexico (see Section 3.18) buries power plant fly ash, bottom ash and centrifuge sludge in mine spoils below the predicted postmining table. Due primarily to the lower permeability of spoils at this latter mine, significant impacts to groundwater quality are not anticipated.

4.3.5 Techniques for Restoration of AVFs

The issue of AVFs began with SMCRA, and therefore the entire technology for their restoration has evolved since 1977.

4.4 Analysis of Criteria for Evaluation of Hydrologic Restoration

4.4.1 Evaluation of Surface-Water Restoration

As described in Section 2.3.3, the statutes and regulations that deal with evaluation of surface-water restoration are quite general (see Table 5). These are keyed to suspended-sediment concentrations, for which baseline data are poor, and to "pollution", which is not quantitatively defined in this context. Most monitoring programs are designed to provide data on streamflow quantity and quality, but these parameters alone will not provide a quantitative basis for the evaluation of restoration.

As illustrated in Case Study 3.19, some operators are attempting to develop methods to relate net sediment production to restoration. The State of Wyoming has recognized that the present surface-water monitoring techniques are not always sufficient to determine the extent of disturbance to the hydrologic balance or to demonstrate that the quality and quantity of runoff from affected lands is such that bond release can be considered (Kearney, in Randen, 1984). To remedy this the State has submitted to OSM a request for funding for a research project to study runoff and sediment production from mined and undisturbed watersheds in relation to precipitation amounts, precipitation intensity and controlling watershed characteristics (Randen, 1984).

From a practical standpoint, the adequacy of surface-water restoration is currently evaluated by observing erosion damage following runoff events (see Sections 3.11 and 3.18). Since design events are generally based on storms with a long recurrence interval (25 to 100 years) and bond-evaluation periods are on the order of 10 years, there is considerable likelihood that a bond could be released before a storm would occur of sufficient magnitude to permit evaluation of the erosional stability of the surface-water system. Therefore at the present time most of the emphasis must be placed on evaluation of the design of the drainage system. As illustrated in Chapter 3 and Table 9, design standards and procedures vary widely among the states, ranging from essentially no design in North Dakota (Case Studies A and D) and New Mexico (Case Study R) to comprehensive designs based on principles of geomorphology and hydraulics in Montana (Case Study E) and Wyoming (Case Studies M and N). However, design requirements also appear to vary within a state (see, for example, Case Studies E and H, Table 9).

A hydrologist for the Wyoming Department of Environmental Quality, Land Quality Division, recently stated that the establishment of stable drainage channels in semi-arid areas is one of the greatest reclamation challenges facing the coal-mining industry (Kearney, 1985).

Mr. Kearney went on to state that, "...most lower order channels in the coal mining areas of Wyoming are currently experiencing some type of instability, such as head-cutting, downcutting, or bank collapse..."

In some states (notably North Dakota and New Mexico, see Table 9) there is a need to increase the emphasis placed on design of restored surface-water systems. Perhaps the development of quantitative evaluation criteria would help in this regard.

4.4.2 Evaluation of Restored Aquifers

Among the regulatory agencies of the western states there are no quantitative requirements in regard to aquifer restoration that must be met in order for a mining company to obtain final bond release. This is probably due to the fact that in many cases the time required for aquifers (including spoil aquifers) to attain hydrostatic and chemical equilibrium in the postmining groundwater systems is unknown but may be many decades or even hundreds of years (see Sections 3.5, 3.12 and 3.19). Methods for predicting the hydraulic characteristics and quality of groundwater in reclaimed spoils are not precise (see Sections 2.4.2.3 and 2.4.2.4). Moreover, it is generally accepted that the quality of groundwater in spoils will eventually improve in time. Accordingly, poor groundwater-quality characteristics that may be observed or predicted in relatively new spoils may not be indicative of the ultimate quality of the water once geochemical equilibrium in spoils has been achieved.

Because of the constraints described above, the technique for evaluating the probable success of aquifer restoration is most often limited to a simple comparison of premining aquifer characteristics with those same characteristics estimated for postmining conditions. In some instances mining companies refer to data from studies of old mine spoils in adjacent or distant mine areas as a means of characterizing probable hydrologic conditions in their own proposed mine spoils (see Case Studies 3.5 and 3.6). The comparisons generally consist of evaluating whether or not postmining groundwater quality will be suitable to support the same uses (stock watering, domestic, irrigation, etc.) as the premining aquifers. The hydraulic characteristics of postmining aquifers are approximately evaluated in terms of potential well yields and the ability of these materials to transmit regional groundwater flow. The overall objective in the comparisons used to evaluate aquifer restoration is to attempt to determine whether or not the postmining aquifers will support premining uses.

The mining company of Case Study F (Section 3.6), as required by the regulatory authority, has expended considerable effort in attempting to measure the recharge capacity of existing spoils and to predict the recharge capacity of proposed spoils. A similar situation exists in the permit application of the mine in Case Study E (Section 3.5). In both cases the concern is with attempting to prove that the reclaimed mine spoils will provide vertical infiltration of water to the groundwater table. As described in Section 2.4.2.4, it is probably not advantageous to have vertical infiltration of waters through spoils, and furthermore, it is likely that for these particular mine areas this component of recharge is negligible in the premining groundwater systems.

4.4.3 Evaluation of AVF Restoration

Evaluation criteria for restored AVFs are described in Section 2.5.3. Specific bond-release criteria for AVFs are summarized in Table 5. Application of these criteria will be facilitated because of the highly quantitative baseline studies used to identify the essential hydrologic functions of the AVF. As with other hydrologic restoration efforts, however, considerable time may be required for these EHFs to reach a postmining equilibrium. Case Study J (Section 3.10) describes how measures may be taken to hasten the reestablishment of the EHFs.

5.0 SUMMARY OF ISSUES

Several issues associated with hydrologic restoration and evaluation technologies for western surface coal mining have been identified in previous chapters of this report. This chapter summarizes these issues and examines whether the regulatory framework is helping to resolve them. Where data or analytical techniques are inadequate to evaluate the success of hydrologic restoration, suggestions are made as to how more or better data can be obtained, how existing data can be better utilized, and how analytical techniques can be improved. This chapter also includes an evaluation of research needs, including options for innovation or experimentation in mining and reclamation technologies.

5.1 Summary of Issues

In each of the case studies presented in Chapter 3 certain issues were identified. These issues are summarized and generally categorized as to whether they are data issues, analytical-technology issues, or evaluation issues in Table 11. Table 11 also identifies the case studies in Chapter 3 that provide the supporting documentation for the particular issues.

5.1.1 Data Issues

As described in Section 4.1, probably the most critical data issue is that monitoring programs have been developed and implemented, sometimes for years, with no specific goals or objectives. Of the data

Table 11. Summary of Hydrologic Issues Identified in Chapter 3

Category	Issue	Case Study
Data Issues	Inadequate use of baseline data.	A, H
	Perfunctory data collection; goals of monitoring program not well defined.	A, B, H, M, T
	Possible redundancy in data collection.	G, H
	Best monitoring program results when specific goals are established.	C, I, J, S
	Need for method to evaluate and manage large and growing database.	G (applicable to all)
	Inequities in amounts of data required.	G, E
Analytical-Technology Issues	Lack of applied technology for surface-water restoration.	A, D, H, Q, R, T
	Uncertainties with respect to spoil-water quality and special overburden handling.	F, M
	Uncertainties with respect to alternative sediment control: How to evaluate vs sediment ponds; inequities in treatment among states and within states.	I, K, also see Section 4.2.1
Evaluation Issues	Lack of established evaluation criteria to determine success of hydrologic restoration.	A, B, E, F, K, M, R, T
	Uncertainty as to when any evaluation criteria will be applied.	B, E, H, J, L, M, N, O, S
	Experimental practice evaluation procedures ignored, or use of experimental practice unequally applied among states.	I, K, Q, also see Section 4.2.1
	Development of guidelines to assist in preparing mine and reclamation plans promotes permitting efficiency and enhances probability of reclamation success.	N

issues listed in Table 11, most would be resolved if mine operators and regulatory personnel would work together to:

1. critically evaluate hydrologic monitoring programs to determine whether the programs have been adequately designed and implemented to achieve specific goals, and make changes accordingly,
2. critique data for accuracy as the data are submitted, and
3. develop a useable data-presentation format that is readable, easily accessible and can be readily updated.

The most prevalent data gap noted in this investigation is the lack of streamflow quality and quantity data for ephemeral streams. This is important if bond-release criteria for TSS are to be applied (see Table 5). Steps being taken in some areas to address this issue are described in Section 4.1.1.

Steps are also being taken in some areas to improve the accessibility and reporting of the increasingly large hydrologic database. One example, though limited to groundwater, is the Gillette Area Groundwater Monitoring Organization (GAGMO), an organization of mining companies which compiles groundwater data collected by its members and publishes them in annual reports. In Montana, the Bureau of Mines and Geology has submitted a proposal to the State to collect all the available hydrologic data submitted by the mining companies, evaluate the data and prepare a computerized database to make the data manageable and readily available to interested persons (Bob Ringler, Hydrologist, Montana DSL, January 2, 1985, personal communication). It is not known when and if this project will be funded. The State of Wyoming recently announced plans to place all groundwater data in the files of the DEQ into the State's computerized information search and retrieval system (Wyoming Department of Administration and Fiscal Control, 1985). This project is expected to take two or more years to complete due to the vast amount of data on file (Dick Lennox, Review Analyst, Wyoming DEQ, March 25, 1985, personal communication).

5.1.2 Issues Regarding Analytical Techniques

As shown in Table 11 three issues which pertain to analytical techniques were identified in the case studies of Chapter 3. A prevailing issue is the lack of applied technology in the design of restored surface-water systems (refer to Section 4.2.1). This issue can only be resolved through an awareness by regulatory personnel that a problem may exist, and subsequent development of guidelines and/or regulations to clarify operator requirements.

Analytical issues regarding spoil-water quality and spoil handling center around the inability, under current technology, to accurately predict spoil-water quality and thereby quantitatively evaluate special overburden-handling techniques which are being required of some operators. Resolution of this issue will require research to improve predictive techniques and development of regulations to clarify, possibly on a site-by-site basis, what degree of groundwater-quality degradation will be acceptable and what type of special handling, if any, will be required to achieve acceptable groundwater quality.

Sediment-control issues center around inequities between states and even between mines within a state in the application of design standards (refer to Section 4.2.1 and Case Studies I and K) and requirements for alternative sediment-control programs. Because sediment-control requirements for surface-coal mines stem from SMCRA, the logical way for this issue to be resolved is for the OSM, through its oversight of state programs, to ensure that minimum sediment-control standards are uniformly developed and enforced by the regulatory authority. Any state is free to adopt its own sediment-control standards provided that these standards are not less stringent than Federal standards.

5.1.3 Evaluation Issues

Surface-water restoration bond-release evaluation criteria are keyed to TSS concentrations and absence of pollution (see Table 5). These criteria are difficult to apply due to baseline data problems (see Sections 5.1.1 and 4.4.1) and to the fact that TSS concentrations in precipitation-runoff is dependent upon many factors. Natural fluctuations and variations in these factors (such as seasonal vegetation characteristics and precipitation frequency-duration relationships) and infrequency of runoff events will always make it difficult to evaluate surface-water restoration in the western United States based on TSS concentrations. A more inclusive set of evaluation criteria are required for surface-water restoration. A large number of case studies were identified in Chapter 3 for which little attention was given to surface-water restoration. Development of pertinent evaluation criteria may focus attention on this subject and therefore improve the probability of reclamation success.

Evaluation of groundwater restoration is centered on the occurrence or probability of occurrence of pollution (see Table 5). Development of a meaningful definition of pollution in this context would help to quantify the goals of groundwater restoration and provide guidance for the establishment and enforcement of equitable requirements for special handling of overburden with undesirable chemical characteristics.

A major issue with respect to evaluation of hydrologic restoration is the time frame required for application of evaluation criteria. Streams designed for a 100-year flood event may not experience significant flow within a 10-year bond-evaluation period, and their erosional stability therefore may not be demonstrated. Spoil aquifers may not resaturate within the bond-evaluation period, so the presence or absence of pollution cannot be ascertained. Because of these time constraints emphasis must remain on design standards and preparation and implementation of adequate mining and reclamation plans. Predictive techniques should be evaluated by reviewing data and updating and refining models and analytical techniques as new information becomes available. Monitoring programs should be critically evaluated to ensure that data are collected with a specific purpose in mind and that data-collection and data-reduction methods are correct.

5.2 Need for Additional Research or Innovative Practices

Based on the information compiled for this report, the following research needs have been identified:

1. Additional research is needed to relate overburden lithology and mining techniques to methods for predicting the hydraulic characteristics of spoil aquifers. The long-term consolidation and settling of spoils, particularly as they

resaturate, and subsequent reduction in spoil permeability also needs to be studied.

2. Additional research is needed to improve and possibly standardize methods for predicting spoil-water quality. In particular, methods should be developed to define toxic and acid-forming overburden for site-specific situations, to quantify how much of this material must be present to mandate special-handling procedures to minimize long-term impacts on spoil-water quality, and to develop objective, technical guidelines to specify what these special-handling procedures should be.
3. A program should be established to utilize collected data for the purpose of verifying and refining predictive techniques such as rainfall-runoff models and groundwater-flow models.
4. Additional research is needed to determine whether alternative sediment control is as effective as conventional sediment ponds, and to define precisely how effectiveness should be determined.
5. Additional research is needed to determine what constitutes toxic and acid-forming overburden when this overburden is placed in proximity to stream channels, and to define the term "proximity."
6. With respect to cumulative hydrologic impacts, many questions remain as to the cumulative effects on groundwater quality of groundwater passing through the spoils of more than one mine.
7. Power-plant wastes are disposed of in a variety of ways (see Sections 2.4.2.4, 3.16, and 3.18). Research is needed to

develop criteria and recommendations for disposal of these wastes.

8. Research should be conducted to develop methods for the determination of recharge by surface infiltration. Although required by statute, more research should be done to determine whether restoration of recharge capacity is really desirable.
9. Research is needed to determine what criteria are needed to quantitatively evaluate hydrologic restoration, and to determine whether development of such criteria would enhance the likelihood of successful hydrologic restoration.
10. Research should be conducted to determine whether spoil-aquifer hydraulics and water quality characteristics could actually be improved through innovative material-handling techniques. Possible examples that may be worthy of study include using available geologic materials (i.e., rock and compacted clay) to construct conduits to convey groundwater through a spoil area to minimize groundwater degradation and enhance restoration of groundwater flow patterns. Another example might be the placement of a granular soil layer below the rooting zone in reclaimed areas. Considering that coarse-grained materials are barriers to unsaturated flow and conduits to saturated flow, this approach could, if properly applied, enhance moisture availability in the rooting zone, prevent water-table problems in the root zone, and possibly eliminate vertical recharge and corresponding groundwater-quality problems.

An interview with a researcher at a state university in one of the states covered by this investigation stated that research funds provided by mining companies for mine and reclamation-related research have declined considerably since about 1980. Examination of publication dates of research reports (e.g., see Table 7) seems to confirm that research activities have recently declined. Reasons for this decline in research funds are not clear, particularly considering the number of uncertainties that remain in hydrologic restoration. If experimental practices represent research by the operators, the fact that only three experimental practices were identified in Chapter 3 (Case Studies C, I and Q) indicates that operators are not performing much research. A major reason is undoubtedly the soft coal market that has prevailed in recent years. One other possible reason, suggested by the university researcher mentioned above, is that the imposition of regulations and performance standards, which more or less dictate how mining and reclamation will be done, have obviated the need for research on the part of the operators to determine how mining and reclamation should be done.

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APPENDIX A

Description of a Computer Model Used to Simulate the Impacts of Surface Coal Mining on the Tongue River, Southeastern Montana

This appendix presents a description of a USGS computer model developed to determine the impacts of surface coal mining on the Tongue River in southeastern Montana (Wood, 1981). For the purposes of this study the Tongue River from near the State line to Miles City (181 miles) was subdivided into five reaches to permit spatial simulation. The study was based upon a hypothetical plan for the mining of all Federally owned coal judged potentially available for mining. This study involved routing of streamflow and dissolved solids using two primary equations. The streamflow balance of a stream reach was computed using a water-budget equation, in which all components of the hydrologic budget were identified and quantified. The dissolved-solids balance of a reach was computed by a mass-balance equation, in which the total dissolved-solids load is determined by multiplying the flow factors identified above by their respective dissolved-solids concentrations.

The water-budget and mass-balance equations are solved for a variety of flow conditions to determine water-quality impacts under dry, normal, and wet conditions. The use of a digital computer enabled the USGS to compute dissolved solids concentrations on a monthly basis for mean flows, plus one and minus one standard deviation from the mean, historic maximum and minimum flows, and "instream" flows (flows necessary for maintenance of the existing physical and biological stream environment).

These equations have data requirements that include both hydrologic components (streamflow from both gaged and ungaged areas, precipitation, evaporation, irrigation withdrawal and return flow, groundwater flow, ice storage and breakup, and other water losses) and dissolved-solids components (streamflow, irrigation withdrawal and return flow, and groundwater). Sources and types of data are described as follows.

Streamflow data were available from USGS gaging stations at several locations along the main stem of the Tongue River and on the major Tongue River tributaries. In-stream flow conditions were obtained from the Missouri River Basin Commission (1978). Streamflow from ungaged tributaries was estimated using areal runoff coefficients calculated from gaged streamflow data. Precipitation and evaporation data were obtained from the Federal Aviation Administration (FAA) and National Weather Service climatological records. Data were not available for actual volumes of irrigation withdrawals and return flows in the study area, and these volumes were estimated by applying agricultural engineering practices to estimates of irrigated acreages (Woessner and others, 1981). Groundwater inflow was estimated from base-flow studies conducted by Lee and others (1981). Using ice-thickness data obtained by the USGS during nine years of streamflow measurements, this model was made to account for the storage of water as ice during the winter and the transformation of that ice into streamflow during the spring. The USGS model is also able to allow for additional water losses from the system, such as might result from additional industrial uses of Tongue River water (Woods, 1981).

Dissolved-solids loads in the USGS Tongue River model are computed by multiplying the volume of a hydrologic component by its associated dissolved-solids concentration. Means of deriving TDS concentrations for gaged and ungaged streamflow, irrigation withdrawal and return flow, and groundwater are described below. The hydrologic components of precipitation, evaporation, and ice storage and breakup, although not associated with a dissolved-solids concentration, do affect dissolved-solids concentrations by addition or removal of streamflow.

For all USGS stream gaging stations, where streamflow and TDS concentrations have been measured concurrently, linear regression equations were derived from historic data to express TDS concentration as a function of streamflow. The regression equations derived for the gaged Tongue River tributaries were used to compute TDS loads from ungaged tributaries. Dissolved-solids loads removed by irrigation withdrawal were computed as the product of the volume of streamflow withdrawn and the TDS concentration in the reach. Dissolved-solids loads from irrigation return flows were based on an assumption of salt balance. That is, all the salt load diverted from the stream for irrigation is returned in the return flow.

Baseline dissolved-solids concentrations for groundwater inflow to the Tongue River were based on values calculated from a 1978 base-flow study of the Tongue River. Dissolved solids leached from backfilled mine spoils were estimated as 1.5 times baseline levels. The dissolved solids leached from the mine spoils were modeled as the quantity entering the streams after such leachates reach steady-state input rates. Based on aquifer characteristics in the study area, the production of leachates may occur for hundreds of years (Woessner and others, 1979). Therefore, the model simulates some undetermined, future time when all coal mines in the study area are discharging at a steady-state rate. In this model, the TDS load from mined areas is calculated using methods developed by McWhorter and others (1979).

Prior to simulating agricultural development and mining plans, the model was tested to determine its accuracy in simulating existing hydrologic and dissolved-solids budgets of the Tongue River study area. Existing conditions were simulated and then compared to historic streamflow and dissolved-solids data. This validation procedure revealed errors in monthly streamflow simulation, and these errors were evaluated to help identify model components in need of additional data. One problem with the data was stated to be the lack of long-term streamflow data on tributaries. Only short-term data (eight years or less) of record were available for tributaries, and these records were used both to compute long-term mean flows on the gaged tributaries as well as to estimate runoff from ungaged tributaries. The ice-related components of the model were the same for all hydrologic conditions simulated (mean, low flow, etc.) due to data limitations. The agriculture-related components are other error sources because only estimates were available for diversions and return flows and even irrigated acreage. Yearly variations in these factors are unknown as well. Groundwater inflow was estimated from a single low-flow investigation. A constant rate of groundwater inflow was estimated for each stream reach because no monthly data were available. Other unknown hydrologic variables included effects of river stage on groundwater inflow and temporary bank storage effects. Despite these data needs, the USGS (Woods, 1981) determined that the hydrologic part of the model is satisfactory, especially during summer months (months of irrigation withdrawal).

The monthly errors in dissolved-solids loads are generally of larger magnitude than monthly errors in streamflow (Woods, 1981). The

USGS is presently obtaining additional data for TDS concentrations for the Tongue River Dam station. The dissolved-solids concentrations of groundwater inflow was estimated from a single low-flow investigation. Intensive studies of alluvial aquifers would be required to provide accurate data on the interaction of the subsurface flow and surface streamflow.

APPENDIX B

Description of Yampa River Basin Cumulative Hydrologic Impact Assessments

This appendix describes two unrelated cumulative hydrologic impact assessments for the Yampa River Basin of northwestern Colorado. The first of these, performed for the OSM, illustrates how such an assessment can be made without the use of a computer model (Kaman Tempo, 1982). The second, performed by the USGS in cooperation with the Colorado Mined Land Reclamation Division (CMLRD), provides a second illustration of the use of a computer model to prepare a CHIA.

For the OSM CHIA baseline streamflow and water quality data were obtained from existing stations operated by the USGS (Yampa River), and the Agricultural Research Service (Fish Creek). Baseline conditions for Trout Creek were obtained from data from McWhorter and others (1979). Data concerning flows and TDS concentrations added by each mine were obtained by Kaman Tempo from the individual mine-permit application documents. These data included NPDES discharge records (for calculation of impacts during mining) and water-quality data from existing spoil monitoring wells together with an assumption of restoration of premining groundwater discharge rates (for calculation of impacts after mining). Where no spoil water-quality data were available spoil-water quality was predicted based on saturation paste extract data. Kaman Tempo used this method to predict spoil water quality based on recommendations by Fred C. Hart Associates (1981).

The OSM CHIA model predicts that the effects of mining on surface-water quality are greatest during periods of low flow when the increased TDS loads from mining are not diluted by surface runoff. The smaller perennial streams are more affected than the Yampa River. The results of the modeling indicate that the cumulative effects of mining on TDS concentrations of the Yampa River and Trout Creek will be negligible during average flow conditions. However, noticeably elevated TDS concentrations may occur in Fish Creek during average flow conditions and in the Yampa River and Fish Creek during low flow conditions as a result of coal mining activities. The elevations in TDS concentrations in the Yampa River during low flow and in Fish Creek during average to low flows could adversely affect the suitability of these waters for irrigation (Kaman Tempo, 1982, p. 2).

Based on the research performed in the Yampa River Basin CHIA, Kaman Tempo made several recommendations concerning data needs for, and the technology of, cumulative hydrologic impact assessments. One of the most difficult aspects of the study was the location of the pertinent hydrologic data in the permit applications for the various mines, leading to the recommendation that a standard technical approach and a standard set of data requirements be established for inclusion in the permit applications. It was also recommended that consideration be given to the use of more sophisticated models for future assessments (Kaman Tempo, 1982).

A computer model to simulate effects of anticipated mining on dissolved solids in Trout Creek and a reach of the Yampa River main stem has been developed by the USGS in cooperation with the Mined Land Reclamation Division (MLRD) of the Colorado Department of Natural Resources (Parker and Norris, 1983). The model is used by the Mined Land Reclamation Division to evaluate the potential cumulative surface water impacts of proposed mines (Candace Thompson, hydrologist for MLRD, personal communication, February 6, 1985). This model, which routes streamflow and dissolved solids through the stream network, was written by A. W. Burns of the U.S. Geological Survey. The algorithm is an accounting procedure that sums water quantity and quality in monthly time steps from one or more upstream points to a downstream point. The addition of water quantity and quality is done at individual points called nodes. A reach is defined as the stream segment between nodes. In the stream network examined in the report, there are 27 nodes. Data can be entered, modified, or outputted at each node.

There are three kinds of nodes: input nodes, internal nodes, and output nodes. Input nodes are the upstream nodes in the stream network. Because the summation process of water downstream starts at these nodes, the ideal case is to have streamflow-gaging stations for the input nodes. Internal nodes are used to input proposed changes in water quantity and quality at individual coal mines. An output node is any node at which there is an interest in observing the model estimates through time and examining differences in these estimates with various anticipated mining activities. The most downstream node usually would be an output node. If the cumulative effects of coal mining in the area upstream from another node are of interest, that node also could be an output node.

For each anticipated mining activity, the Colorado Mined Land Reclamation Division estimated flows and dissolved-solids concentrations for water discharging to the stream from the mining activity using information provided in mine plans.

In addition to providing a means of estimating hydrologic impacts of mining, the USGS model of Trout Creek helped to identify data-collection needs. Mean monthly observed discharges were required for seven input nodes. Observed data for the entire study period (1976-1981) were available for only four of these. Partial record was available for one other node, requiring that missing data be estimated by correlation to extend the record at that node. For the other two input nodes no streamflow information was available, and records for these two stations had to be estimated. The model study identified data collection needs, particularly for streamflow data at the mouth of Trout Creek, water-quality data at the model outlet node, and both streamflow and water-quality data for the tributaries north of the Yampa River main stem.

APPENDIX C

Overview of Techniques for the Calculation of Pit-Water Inflows and Resulting Groundwater-Level Drawdowns

This appendix presents a brief overview of typical analytical techniques used to compute pit-water inflows to surface coal mines and resulting drawdowns in the potentiometric surface surrounding the pit. The prevailing methods are described in terms of their theoretical basis, data requirements, and their relative advantages and disadvantages. Examples of the use of most of these methods are provided in the case studies of Chapter 3. The methods range in complexity from a simple extrapolation of historic data from an existing mine (refer to case studies in Sections 3.2 and 3.6 of Chapter 3) to sophisticated digital computer models.

The simplest computational technique for predicting pit inflows and resulting drawdowns is an application of Darcy's Law (Lohman, 1979, p. 10). Darcy's Law states that the rate of laminar flow of water through a porous medium is proportional to the hydraulic gradient. Application of Darcy's Law requires the inherent assumptions of laminar (viscous), steady flow, homogeneous aquifer material, and that the base of the aquifer and the water table are parallel. The accuracy of the use of Darcy's Law is a function of how nearly these assumptions are met. Because the slope of the water table varies sharply in the vicinity of the highwall, the Darcy equation can provide unreliable estimates of pit inflow if not properly used. One problem with the use of this method in predicting pit water inflows and drawdowns is that there are two unknowns (flow and gradient) which must be solved with only one equation. Therefore, to use this method one generally has to assume a hydraulic gradient and then solve for the flow. This is done by assuming the location of the seepage face in the exposed pit and then computing the gradient between that point and a point distant from the pit face where water levels are not expected to be affected. The area of the aquifer that will contribute flow to the pit is then determined and, using a permeability value determined from aquifer tests, the Darcy equation is solved for flow into the pit. If data from an existing pit are available to calibrate the equation, acceptable results can be obtained with this simple technique, but for a new mine the results obtained are approximate at best.

For many mines a better approximation can be obtained with the use of radial-flow equations such as the Theis nonequilibrium equations (Lohman, 1979).

The Theis non-equilibrium equations are based upon the following assumptions:

a. the aquifer is everywhere homogeneous and isotropic,

b. well diameter is small compared to the distance at which drawdowns are being calculated,

c. the well is fully penetrating,

d. there is no leakage of water into the aquifer of interest from underlying or overlying formations, and

e. water is released instantaneously from storage with a decline in head.

Although the Theis equations were developed for non-leaky, confined aquifers, adjustments can be made to account for unconfined aquifers or leaky, confined aquifers (Walton, 1969, pp. 4-7). The use of the Theis non-equilibrium method infers that the mine pit simulates a large well, and flow occurs radially toward the center of the pit. For the initial opening of a pit, when radial flow can occur, the Theis equation can give reasonably good results. As with the Darcy equation, however, both flow and drawdown are initially unknown. Generally, the investigator will assume a drawdown at the pit face and compute the resulting flow using the Theis equations. Aquifer parameters are those obtained from analysis of pump tests. Since unrealistically large pit inflows would result from "instantaneous" opening of the pit, it is customary to assume that the pit opens in several stages, and a separate set of calculations is performed for each stage.

A surface coal mine is actually a continuously "moving hole", with overburden from successive cuts being replaced in the preceding cut. Therefore, even if the pit can initially simulate a large well and if the assumptions on which the Theis equations are based are reasonably appropriate, this changes as mining proceeds. A variety of methods are available to adapt the Theis equations to this "moving well" condition. One method is to account for the initially dry spoils behind the pit by merely assuming that radial flow occurs toward the pit from only some portion of a circle, and no flow comes from the dry spoils behind the pit. The flow is reduced accordingly, although the full flow is still used to predict drawdowns in the undisturbed portions of the affected aquifers.

Results obtained with the use of the Theis equations should be reasonably accurate if no hydrologic barriers or boundaries are encountered within the cone of depression that surrounds the pit and the aquifers are reasonably homogeneous. If a recharge boundary exists in the vicinity of a pit, then the calculated drawdown values must be reduced accordingly. If a barrier boundary is encountered, drawdowns beyond that boundary will be overestimated by the Theis equations unless adjustments are made, and drawdowns between the barrier and the pit will be underestimated.

When aquifer boundaries are encountered the assumption that the aquifer is of infinite areal extent no longer is met. Analysis of this situation involves the principle of superposition, by which the drawdown of two or more wells is the sum of the drawdowns of each individual well. By introducing imaginary (or image) wells, an aquifer of finite extent can be transformed into an infinite aquifer so that the Theis equations can be applied (Todd, 1976, p. 139). Imaginary recharge wells (the reverse of pumping wells) can be used to simulate a constant-head boundary, such as a stream or an aquifer with a very large permeability compared to the aquifer being affected by the pumping well (or pit in this case). Imaginary pumping wells can be used to simulate a barrier boundary by placing them across the boundary and at a distance from the boundary equal to that of the pit. An example is provided in Section 3.14.

Another analytical technique used for the determination of pit inflows is the use of a one-dimensional flow equation for a fully-penetrating excavation developed by the Department of the Army, Navy and Air Force (1971). The equation assumes that the sources of recharge and the mine pits are infinite in length and parallel, and that recharge, which must equal pit flow, is from the line sources. Thus, no drawdown can occur beyond the line sources. In reality, flow at the ends of the pits for some distance will be greater, and the drawdowns will be less than predicted for the central portions of the pits.

Potentiometric-head declines in the affected coal aquifer can be computed using a one-dimensional equation (Departments of the Army, Navy and Air Force, 1971) similar to the preceding equation under the assumption that the coal aquifer will remain largely confined in advance of the mine pits. The assumption of confined aquifer flow is valid in most areas because the permeability of the coal is usually low.

Another commonly used method to compute pit inflows employs equations developed by Jacob and Lohman (1952) and Stallman (1962) and is based on the assumption that total pit inflow is derived from two principal sources: 1) removal of water from aquifer storage through radial flow to the corners of the pit; and 2) removal of water from aquifer storage through linear flow to the longitudinal sections of the pit. In itself this method computes only the quantity of water yielded from aquifer storage and does not include the component of pit inflow derived from the down-gradient movement of groundwater. Accordingly, although it is not always addressed in mine-permit applications, the radial and linear storage release method must be combined with use of a one-dimensional gradient flow equation, such as the Darcy equation, to provide an accurate prediction of the total quantity of pit inflow.

The use of digital computer models in mining hydrology is increasing. Data collection for digital computer groundwater-flow models involves the conducting and analysis of aquifer tests or collection of existing hydraulic information. The amount of data required depends primarily on the size and complexity of the system being modeled.

Data preparation for digital models involves determining the boundary conditions and discretizing the region being modelled into a rectangular grid (for finite-difference models) or irregular polygons (for finite-element models). The difference between these types of models is discussed in a later section of this appendix. Once the subdivision of the system is completed it is necessary to specify aquifer parameters and initial data for each grid node or polygon.

Initial estimates of aquifer parameters constitute the first step in a trial-and-error history matching procedure (model calibration), which is used to refine initial estimates of aquifer properties, determine boundaries (the areal and vertical extent of the aquifer), and the flow conditions at the boundaries. Usually, steady-state (or equilibrium) heads must be determined and used as initial conditions (Faust and Mercer, 1980c). Simulated wells (mine pits) are then allowed to pump at observed or specified rates, and computed (simulated) drawdowns are compared with observed (or reasonable) drawdowns. Assuming that the model is correct, the drawdown comparison indicates the accuracy of the input data. It is usually necessary to modify some of the input data until all observed and calculated data compare sufficiently well. Usually this is done by trial and error. Recently the amount of work in matching has been reduced somewhat by using parameter estimation methods, or identification models (Bachmat and others, 1980, p. 20), that modify initial estimates of input data in an objective fashion. Once completed, the model can be used to predict the future behavior of the aquifer. Accuracy of the predictive results is variable and dependent on model limitations, the accuracy of the calibration, reliability of input data, and characteristics of individual aquifers (Faust and Mercer, 1980d). Models can be run with any amount of available data, but the quantity and quality of these data will determine the reliability of the model's results. Sometimes an important use of a model is to identify areas where data are lacking.

Groundwater flow models in general use are either finite-difference or finite-element models. Use of a finite-difference model (FDM) requires subdivision of the study area into a grid system. Associated with the grids are node points that represent that position at which the solution of unknown values (head, for example) is obtained. In mesh-centered grids the nodes are located on the intersection of grid lines, while in block-centered grids the nodes are centered between grid lines. The choice of the type of grid use depends largely on the boundary conditions; from a practical point of view the differences in the two types of grids are minor (Faust and Mercer, 1980e). The FDM provides approximate numerical solutions to partial differential equations of flow by differentiation.

Finite element models (FEM) provide an approach to the solution of partial differential equations based on integration. The FEM actually refers to the numerical method whereby a region is divided into subregions called elements, whose shapes are determined by a set of points called nodes. The FEM is more flexible than the FDM in that it enables consideration of regimes with complex geometry. The FEM has a more advanced mathematical basis and can provide higher levels of accuracy, but data input and programming are more difficult. Using the FDM data input and changes to the program are more easily accomplished, but the relatively low accuracy of predictive results are unacceptable for some applications. This distinction between the accuracy of the FEM and FDM methods is probably not a serious item when considering the accuracy of the available data and the limited data available for large areal regions.

The user of numerical models must be concerned with accuracy, efficiency and stability. Accuracy is a measure of how well the discretized solution approximates the solution to the continuous problem it represents. Efficiency is a measure of how much computational work and computer resources are required to obtain a solution. Stability addresses the question of whether or not a solution is possible at all (Faust and Mercer, 1980b). Numerical models should be expected to serve only as qualitative guides to behavior of an aquifer under various stresses, but more often than not are used as quantitative tools.

Both FDM and FEM have their advantages and disadvantages. Although selection of the model is best made to correspond with the physical system being modeled, it is more commonly made to fit the user's experience or computer system. The FDM is more widely used today, but there is a general perception among computer modelers that the newer FEM is a superior analytical technique and will eventually be the predominant type of model for analysis of groundwater flow (Dick Bloyd, USGS Water-Resources Division, January 11, 1985, personal communication).

The input necessary to solve a model of the kind developed by Prickett and Lonnquist (1971) and Trescott and others (1976) consists of a definition of boundary conditions, transmissivity, storage coefficient, and recharge.

Definition of boundary conditions is one of the most difficult problems in designing a model. Natural boundaries, such as major groundwater recharge or discharge areas or impermeable boundaries, may be too far from the modeled area to be included. A common practice is to make the modeled area large enough so that errors in the boundary conditions will have little effect on the heads in the interior portion of the grid. If this is done, the sensitivity of the model to changes in boundary conditions should be determined. Physical, realistic boundary conditions should be used whenever possible.

It is uncommon to have field values of transmissivity (T), storage coefficient (S), and recharge (R) for each node in the system. Usually, only a few values for T and S will be available from pumping test data for the entire modeled area. This information is used together with information on stratigraphy and specific capacity (the ratio of discharge rate to drawdown) from well logs to estimate the distribution of T and S over the grid. Values of areal recharge rate can only be determined roughly based on the amount of precipitation and evapotranspiration. Pumping rates of wells must also be considered when specifying values for R.

For steady-state simulations any set of initial guesses for head can be selected. The better the guesses, the fewer the number of iterations that will be required for the solution to converge. For transient simulations (changing flow and head conditions), it is common to use a steady-state head configuration as the initial conditions. Trescott and others (1976, p. 30) pointed out that "....if initial conditions are specified so that transient flow is occurring in the system at the start of the simulation, it should be recognized that water levels will change during the simulation, not only in response to the new pumping stress, but also due to the initial conditions. This may or may not be the intent of the user."

In general, the first step in model calibration is to design a steady-state model to solve for the head distribution to be used as the initial conditions in a later transient simulation. Given the input data discussed in the previous section, it is possible to generate a solution for the heads at each nodal point. However, in order to verify the accuracy of the solution, it is necessary to match the computed heads with heads measured at a number of points in the field. Invariably, the heads computed from the first run of the model will not match the field values. Calibration consists of adjusting the input data until computed heads match the field values. It is not unreasonable to adjust the input data because these data are imperfectly known, and there will be a range of values that may be valid. It is not uncommon to make from twenty to fifty trial-and-error simulations before an acceptable calibration is achieved.

Novice modelers are often tempted to use the measured values of head as input to the model. That is, the temptation is to force heads in the interior of the grid to equal the field measured values in the hope that this will ensure calibration. However, if the boundary conditions and values for T, S, and R are not specified correctly, this procedure will result in the creation of artificial sources and/or sinks in the interior of the grid, and the resulting head configuration will be unrealistic.

Calibration means that, given a certain combination of parameters and boundary conditions, the model will produce field-measured values of head at certain points in the grid. However, there is no guarantee that the combination of parameters found by trial and error is unique. Different hydraulic conductivity distributions will produce essentially the same head distribution. When better methods of solving the inverse problem are perfected, it may be possible to find an optimum solution for transmissivity.

The goal of verification is to demonstrate that the model is capable of simulating some historical hydrologic event for which field data are available. For example, one might attempt to simulate drawdowns during a pumping test, water-level declines during a drought, or historic drawdowns due to pit dewatering. Generally, some additional refinement of parameters will be necessary during verification. These refinements should not change the steady-state calibration. After the model has been calibrated and verified, it is ready to be used for prediction.

The FDM of Trescott and others (1976) was used by the USGS to model the Anderson-Dietz coal aquifer in the West Decker area of Montana. The area was divided into a finite-difference grid having 21 rows and 27 columns (Davis, 1984). Nodes were located at the centers of the grid blocks, which are 0.25 miles on a side. The grid, which is oriented in northwest and northeast directions, alines with the major and minor axes of hydraulic conductivity. This was necessary because the hydraulic conductivity of a coal aquifer is due primarily to fractures, or cleat, in the coal. The fractures oriented perpendicular to the strike are the most continuous, which results in anisotropic hydraulic conductivity (Stone and Snoeberger, 1977, and Stoner, 1981).

Several types of boundaries were used in the USGS model. The computer program requires that the area be surrounded by a no-flow boundary consisting of nodes at which the transmissivity equals zero. Along fault zones, the no-flow boundary simulates actual conditions because the faults in this area are barriers to groundwater flow. In other areas, a constant-head boundary (simulating the Tongue River and Tongue River Reservoir), a head-dependent variable-flow boundary, or a constant-flow boundary was placed inside the no-flow boundary of the model.

Most of the geohydrologic data used by the USGS in their groundwater flow model of the West Decker area were previously published by the Montana Bureau of Mines and Geology (Van Voast, 1974, Van Voast and Hedges, 1975, and Van Voast and others, 1977, 1978). Water-level measurements were available for 92 wells, of which 68 were completed in coal, three in clinker, two in interburden, five in overburden and 14 in replaced spoils. Results of 16 aquifer pumping tests conducted in coal aquifers and six aquifer pumping tests conducted in spoils were available from the Montana Bureau of Mines and Geology (Van Voast and others, 1978).

Steady-state calibration of the model consisted of adjustment of the values of the hydrologic parameters, which govern the groundwater flow, until the calculated head distribution accurately simulated the measured head distribution. Although data on recharge were not known, assumed values of 0.6 inch for areas underlain by clinker and alluvium and zero for all other areas produced the closest match of calculated to observed hydraulic heads.

The mean difference between observed hydraulic head and the hydraulic head calculated by the calibrated steady-state premining model simulation was -0.03 foot. The absolute value of the difference at any one node was less than 10 feet. These small differences indicated that model calibration was adequate (Davis, 1984, p. 29).

The USGS determined through sensitivity analyses that the model is most sensitive to changes in hydraulic conductivity and least sensitive to changes in recharge, probably because of the localized extent of the recharge area in this particular region. The USGS did state that if data-collection activities occur in the future it would be useful to consider determination of hydraulic conductivity for additional areas and the ratio of anisotropy, which was an assumed value for this study. Additional data on spoil aquifer hydraulic conductivity are also needed.

By the use of this model the USGS was able to predict that at postmining equilibrium, water levels west of the West Decker Mine probably will increase almost 12 feet over premining levels, although the increases diminish within several miles of the mine. These postmining increases are ascribed to the damming effect of the relatively less permeable spoils on regional aquifer flow. It is also predicted that about 13 years will be required for water to flow from the spoils to the Tongue River Reservoir. Using the results of the flow model together with estimates of groundwater quality effects of mining, the USGS also was able to predict that the increase in dissolved-solids contribution to the reservoir due to mining will be less than one percent (Davis, 1984, p. 59).

Digital computer models are not an appropriate analytical technique in every instance. For example, the USGS was unable to produce a verifiable, calibrated groundwater flow model of the Powder River Basin coal-mining area near Gillette, Wyoming. This study was requested, and partially funded, by the Wyoming regulatory authority as a part of their obligation to perform a cumulative hydrologic impact study of this area. Due to the time and budget constraints the USGS simplified the groundwater system to three separate aquifers: overburden, coal and underburden. While part of the reason for lack of success may have been the lack of adequate time and money, the unsuccessful model study caused the USGS to question whether the area could be modeled (Dick Bloyd, USGS Water-Resources Division, January 11, 1985, personal communication). The USGS report on this study is not yet available.

APPENDIX D

Overview of Techniques for the Prediction of Spoil-Water Quality

This appendix provides an overview of the currently prevailing techniques used to predict water quality in the replaced spoils at western surface coal mines. Two general approaches are described. One approach involves measuring water-soluble constituents in spoils through batch-leach tests, saturated paste extract analyses, or column-leach tests and then relating the measured values to spoil-water quality. The second general approach is based on a rigorous analysis of the chemical processes responsible for spoil-water quality.

Batch-mixing studies were conducted by the USGS (Davis, 1984) to simulate changes in groundwater quality that may occur as a result of mining operations in the West Decker area of Montana. Several weight-ratio combinations of water and rock material taken from various parts of the study area were mixed for about two hours. Mixing was accomplished by affixing the mixture bottles, which were filled to exclude oxygen, to a vertical wheel that is three feet in diameter, rotating at three revolutions per minute. The mixtures were then allowed to settle and were filtered after a total contact time of about 24 hours. The water used in the batch-mixing tests was obtained from the coal bed. When the water-to-spoils ratio was 2:1 by weight, the increase in dissolved-solids concentration in the water was similar to that observed to some wells in the area. A mixture of 5:1 (water:spoils) showed smaller increases in TDS, indicating that the amount of soluble material was the limiting factor (Davis, 1984, p. 39). The amount of water in a 2:1 mixture of water and spoils material represents almost 900 effective pore volumes (the volume of water potentially held in a unit volume of spoils); the 5:1 mixture represents almost 2,200 effective pore volumes. The passage of 900 effective pore volumes would take 5,400 years in the West Decker spoils under the assumed conditions of hydraulic conductivity, gradient, and width of the spoils aquifer. The passage of 2,200 effective pore volumes would take about 13,000 years (Davis, 1984, p. 40).

Batch-mixing tests were also used by the Kerr-McGee Coal Corporation to estimate spoil-water characteristics at the Jacobs Ranch Mine (Kerr-McGee Coal Corporation, 1983). These tests were done using a water:soil ratio of 4:1 and a test period of 48 hours as prescribed by ASTM Test No. D3987-81. The elution water was taken from a well completed in the coal aquifer and was purged with nitrogen to remove dissolved oxygen to simulate spoil water. A second study was performed using aerated elution water to determine whether dissolved oxygen in the elution water would affect the concentration of dissolved solids in the water. No significant difference was found. However, the operator noted that the spoil material had no significant acid-forming potential (Kerr-McGee Coal Corporation, 1983, Addendum D6P).

McWhorter et al. (1975) reported that the dissolved-solids concentrations of spoil leachates can be estimated using the saturated-paste extract method of analyzing overburden materials. The procedures used are those described by Hergert (1971). The sample is first completely dried and then the material is reduced in size to the point where it will pass a 2-mm screen. The sample is saturated with distilled water, thoroughly mixed, and allowed to stand for 16 hours. The saturation percentage is determined on a portion of the sample by normal gravimetric techniques, and the water is extracted from the remainder of the sample and analyzed for chemical constituents.

Van Voast and Thompson (1982) also used the saturated-paste extract method to predict spoil water quality for mines in the Tongue River Basin of Montana and Wyoming. This method was used because saturated-paste extract data are readily available and because they show a statistical correlation with analyses of actual spoils waters. For this study, it was assumed that the concentrations of cations in overburden-paste extracts would represent additions to natural concentrations of these cations in the groundwater reentering and eventually discharging from the mine spoils. Anion concentrations, unavailable because they are not routinely determined from paste extracts, were estimated by assuming that chloride contents would remain insignificant, that increased bicarbonate and sulfate concentrations would be in the same relative proportions as those in natural groundwater near each mine, and that cation-anion balances would be maintained. For these analyses, dissolved-solids concentrations were calculated by summing the concentrations of calcium, magnesium, sodium, sulfate, and 0.4917 (a constant determined from regression) times the concentration of bicarbonate, thereby simulating dissolved-solids concentrations that would be calculated from an actual water analysis (Van Voast and Thompson, 1982, p. 3). Data on overburden analyses, available in mine-permit applications for 122 samples from the Big Horn Mine, 50 samples from the Welch Mine, 74 samples from the Whitney Benefits Mine, 164 samples from the Pearl Mine, 283 samples from the CX Ranch Mine, 151 samples from the West Decker Mine, 203 samples from the East Decker Mine, 120 samples from the North Decker Mine, and 20 samples from the Spring Creek Mine, were utilized. Based on these data it was estimated that dissolved-solids contents in postmining groundwater would increase from 63 percent at the CX Ranch Mine to 300 percent at the North Decker Mine. The most substantially increased concentrations would be those of sodium, sulfate, and bicarbonate. It was observed that as water from the spoils aquifer flows through adjacent coal beds, the processes of cation exchange and sulfate reduction are active enough to remove nearly all the calcium, magnesium, and sulfate from solution within only a few miles of recharge areas. In this manner the concentration of dissolved solids in waters from spoils areas separated by coal beds from recharge areas is substantially reduced (Thompson and Van Voast, 1981).

Column-leaching tests are another widely used technique for predicting the total quantity of soluble materials in spoils, and have the added advantage of determining the relationship between dissolved constituents and water through-put volume. There is no standard method for performing column-leach studies. Generally, water is forced upward through columns containing overburden samples to maintain saturation and restrict channeling. Samples are drawn off at periodic intervals to determine the relationship between dissolved constituents and pore volumes of water leached. Water used in such studies may be de-ionized water or water from an aquifer in the mine vicinity. The columns may be open to the atmosphere or closed, with the driving head being applied with pressurized nitrogen bottles. An example of a column-leaching study is presented in Case Study 3.15 in Chapter 3. Column-leaching studies can provide an indication of the water quality in the initial wetting front that will move through the spoils, as well as providing a means of estimating the number of pore volumes that will be required for the spoil water to reach equilibrium with the spoil materials.

Comparison of column leach test data with saturated paste extract data indicated that concentrations of major ions in saturated paste extracts were very similar to the values obtained for the first pore volume of extract obtained from column leach tests (Van Voast and others, 1978). The cost of column-leach tests is much greater than that of obtaining saturated paste extracts. Therefore, with the similar results and disparity in cost, Van Voast recommends using saturated paste extracts for continued work on the prediction of spoil-water quality. Also, analysis of saturated paste extracts is a commonly required overburden analytical technique in the western United States with data already available at various mine sites.

In an approach that utilizes rigorous geochemical analysis to predict spoil-water quality, the U.S Geological Survey is currently working with three computer models (Dave Naftz, USGS geochemist, January 11, 1985, personal communication). These three models, together with water quality and overburden data collected by the USGS and by operating coal-mining companies in the Powder River and Hanna basins, have been used by the USGS to determine statistical and geochemical trends in spoil water quality in these areas. The computer models are described below.

WATEQF (Plummer and others, 1976) is a program that calculates the thermodynamic speciation of inorganic ions in solution for one or more water analyses. Saturation indices of approximately 120 minerals are calculated for testing possible mineral controls on water composition. Data requirements for this model are a chemical analysis of the water, including pH, temperature, and major species. WATEQF was used by Davis (1984) to determine the equilibrium relationships in water from observation wells in the West Decker and Big Sky coal-mining areas of Montana. Saturation or supersaturation with respect to a given mineral species implies the possible presence of that mineral species in the aquifer. Undersaturation with respect to a mineral species implies that the groundwater has limited contact with the mineral species. This knowledge, coupled with mineralogic data, can help in determining the hydrological and geochemical processes occurring in the hydrologic system.

BALANCE (Parkhurst and others, 1982) is a computer program for calculating mass transfer of geochemical reactions in groundwater. This program is used to calculate the amounts of minerals which must dissolve or precipitate to account for observed differences in water composition along a flow path. Data requirements include chemical analyses for two waters along a flow path and a knowledge of minerals in contact with the water that are likely to form from the water.

PHREEQE (Parkhurst and others, 1980) is a computer program designed to model geochemical reactions. Based on an ion pairing aqueous model, PHREEQE can calculate pH, redox potential, and mass transfer as a function of reaction progress. The program is capable of mixing waters, equilibrating waters with multiple phases, including gases, and simulating redox reactions. The composition of the water following the reaction, including pH and pE (measure of the redox potential), is computed. Data requirements are chemical analyses for all major constituents in a water.

Several researchers in North Dakota are developing another method for predicting spoil-water quality based on a complete understanding of the chemical processes involved. These people are convinced that the saturation-extract method estimates only the short-term spoil-water quality. Their calculations include the long-term salt-generation capacity of spoil waters (Fred C. Hart Associates, 1981). The work on this predictive method is primarily being conducted within the Fort Union Region of Western North Dakota by researchers at the North Dakota Geological Survey.

The conclusion that the saturation-paste extract method cannot be used to predict long-term water quality was based on the fact that this type of test does not indicate the salt-generation capacity (which is a function of the abundance of the oxidizable pyrite) of the spoil materials but only the salinity (the presence of soluble salts). It was also concluded that in order to assess the chemical conditions on a long-term basis, it will be necessary to develop analytical techniques to determine calcite content at very low levels of concentration, abundance of potentially oxidizable pyrite, and actual ion-exchange characteristics under field conditions (Moran and others, 1978).

The term "engineered cast overburden" (ECO) was coined in North Dakota to refer to an approach to reclamation of surface-mined lands and is defined as reconstruction of the entire landscape rather than just its surface form and soil (Moran, Groenewold, and Cherry, 1978). This approach to control of postmining groundwater chemistry requires a thorough understanding of several geochemical and mining processes as well as the development of a number of analytical techniques. Materials comprising the overburden must be identified and evaluated. The inventory involves soil mapping, geologic mapping, development of a three-dimensional materials framework, geohydrological studies, and geochemical studies to delineate the properties of the materials. The investigators state that an understanding of the form and internal structure of material deposited by various types of mining equipment and techniques is necessary to determine which equipment and procedures could be used to obtain desired physical and chemical characteristics at desired locations within the cast overburden.

In the study by Moran, Groenewold, and Cherry (1978), the chemistry of overburden core and cutting samples was analyzed at five mine sites. Over 500 saturation extracts were analyzed. Additionally, the quality of the groundwater was evaluated, and relationships between overburden type and water quality were evaluated.

Four significant chemical-property trends of overburden materials were identified from the analyses: (1) materials having a higher clay content have a greater tendency to be sodic; (2) the proximity of the materials to the land surface, regardless of texture, has a strong influence on their chemical characteristics; (3) the direction of groundwater movement in the near-surface zone in large part controls the chemical characteristics of the materials; and (4) it is very likely that geochemical variations in the materials of the original environment of deposition and interaction with groundwater flow have a strong influence on the chemical characteristics of the overburden materials (Moran, Groenewold, and Cherry, 1978).

To determine the postmining quality of groundwater, the authors based their analysis on the assumption that "an interpretive framework that adequately accounts for the observed water chemistry in the natural overburden will have some applicability in the analysis of salt generation and accumulation in reclaimed land." To be valid, this framework must account for several variables, including the existence and variation of the predominant ions in the subsurface water, the pH of the water, variation in the concentration of total dissolved solids of the groundwater, and the partial pressure of dissolved carbon dioxide in the water. It must also account for changes in water chemistry that occur as the water infiltrates and migrates through the underlying vadose zone into the groundwater zone.

The studies in North Dakota for ECO reclamation techniques resulted in the development of a hydrogeochemical model which accounts for the observed chemical characteristics of subsurface water in both disturbed and undisturbed settings. Critical hydrogeochemical processes were determined to be sulfide oxidation, gypsum precipitation and dissolution, carbonate mineral dissolution and cation exchange. Alternate wetting and drying in the near-surface several meters of the landscape was determined to be a key mechanism in hydrogeochemical evolution. Groenewold and others (1983) concluded that their hydrogeochemical model is equally applicable to undisturbed and spoils landscapes and that the major species of concern are sodium and sulfate. Sulfides were determined to be the major source of sulfates, and the solubility of sulfate in groundwater was determined to be largely controlled by the sodium/calcium ratio. It was determined that the worst impacts on postmining groundwater quality would result from placement of unoxidized sodic and sulfide-rich sediments near the surface and above the water table where water from surface infiltration could contact these sediments en route to the groundwater table. Placement of these materials below the postmining water table can result in short-term degradation of groundwater, but over the long term will prevent oxidation of the sodic and sulfide-rich sediments and water quality will improve after initial flushing of soluble salts.